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HYDRAZINE APU STARTER DESIGN

ROCKET RESEARCH COMPANY
YORK CENTER
REDMOND, WASHINGTON 98052

NOVEMBER 1977

FINAL REPORT FOR PERIOD NOVEMBER 1976 – NOVEMBER 1977

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This report has been reviewed by the Information Office (ASD/OIP) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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The purpose of this program was to design a hot gas motor that would subsequently be used as the prime mover in an advanced aircraft auxiliary power unit starter system.

The report describes the APU starter system approach and the design details of the hot gas motor. The hot gas motor is a rotary vane device that would be powered with the decomposition products of a hydrazine-based fuel blend.

Two computer models are presented for predicting the thermal-structural and thermal-performance characteristics of the hot gas motor over the required ambient temperature range of -65 to +130°F.

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FOREWORD

This report summarizes the design and analysis activities associated with the preparation of detailed manufacturing drawings for a rotary vane type hot gas motor that would subsequently be used as the prime mover in an advanced hydrazine-fueled aircraft APU starter system.

The work described herein was directed by Mr. L. D. Galbraith of Rocket Research Company, Redmond, Washington. The project was sponsored by the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio, under Project, Task and Work Unit No. 31450134 with Mr. B. L. McFadden, AFAPL/POP, as Project Engineer in charge.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Concluded)

LIST OF TABLES

SECTION I
INTRODUCTION

This report summarizes the results of the design and analysis activities associated with the preparation of detailed manufacturing drawings for a rotary vane type hot gas motor that would subsequently be used as the prime mover in an advanced hydrazine fueled aircraft APU starter system. The work described herein was conducted under Wright Patterson AFB Contract F33615-76-C-2148.

CURRENT APU STARTING SYSTEMS

Current military aircraft auxiliary power units (APU's) are generally started with either a battery powered electric motor or a pneumatic accumulator driven hydraulic motor. At low temperatures (-49 to -65°F) these systems are hard pressed to provide sufficient stored energy for even one start attempt. The hydraulic approach does permit the flight crew to "pump up" the system by hand for a second start attempt; but several inherent disadvantages of this pneumatic hydraulic system are evident, as verified by field experience.

Weight – The pneumatic-hydraulic starter system typically weighs in excess of 120 pounds because large reservoirs are required to contain the high pressure gases that expel the hydraulic fluid.

Size – Because of the large volume required for gas storage, pneumatic-hydraulic starter systems consume a significant amount of valuable storage space within the aircraft.

Low Temperature Performance – The starting requirements (starting torque versus speed) of a typical APU become very demanding at lower temperatures, and the power output characteristics of the pneumatic-hydraulic systems are marginal at -20°F. Since military aircraft are typically designed for -65°F operation, the current hydraulic systems are unacceptable.

One-Shot Capability – Even though the pneumatic-hydraulic starter systems are equipped with a hand pump for manual system recharge, the time required to recharge the system is not acceptable for rapid sequential start attempts if the APU does not start on the first attempt.

ADVANCED APU STARTING SYSTEM

A review of the problems and shortcomings of the current pneumatic-hydraulic APU starter concept has led to the definition of an advanced APU starter system approach that would utilize hot gas generated by the decomposition of a hydrazine based fuel blend to power a hot gas motor which would be used as the prime mover to start the APU.

The major benefits to be derived from this advanced system include:

1) Reduced system weight
2) Reduced system volume
3) Multiple start capability with minimal time between restart attempts
4) True -65 to +130°F system operating characteristics

STATE OF THE ART

In order to implement the advanced hydrazine fueled APU starter concept, a review of the developmental status for each component in the proposed system must be conducted to assess the risk of committing funds for future feasibility demonstration test programs. This review has been conducted and may be summarized as follows:

1) The basic hydrazine technology exists and has been demonstrated.
2) The basic technology exists for the design and fabrication of each system component with one exception, that being the hot gas motor.

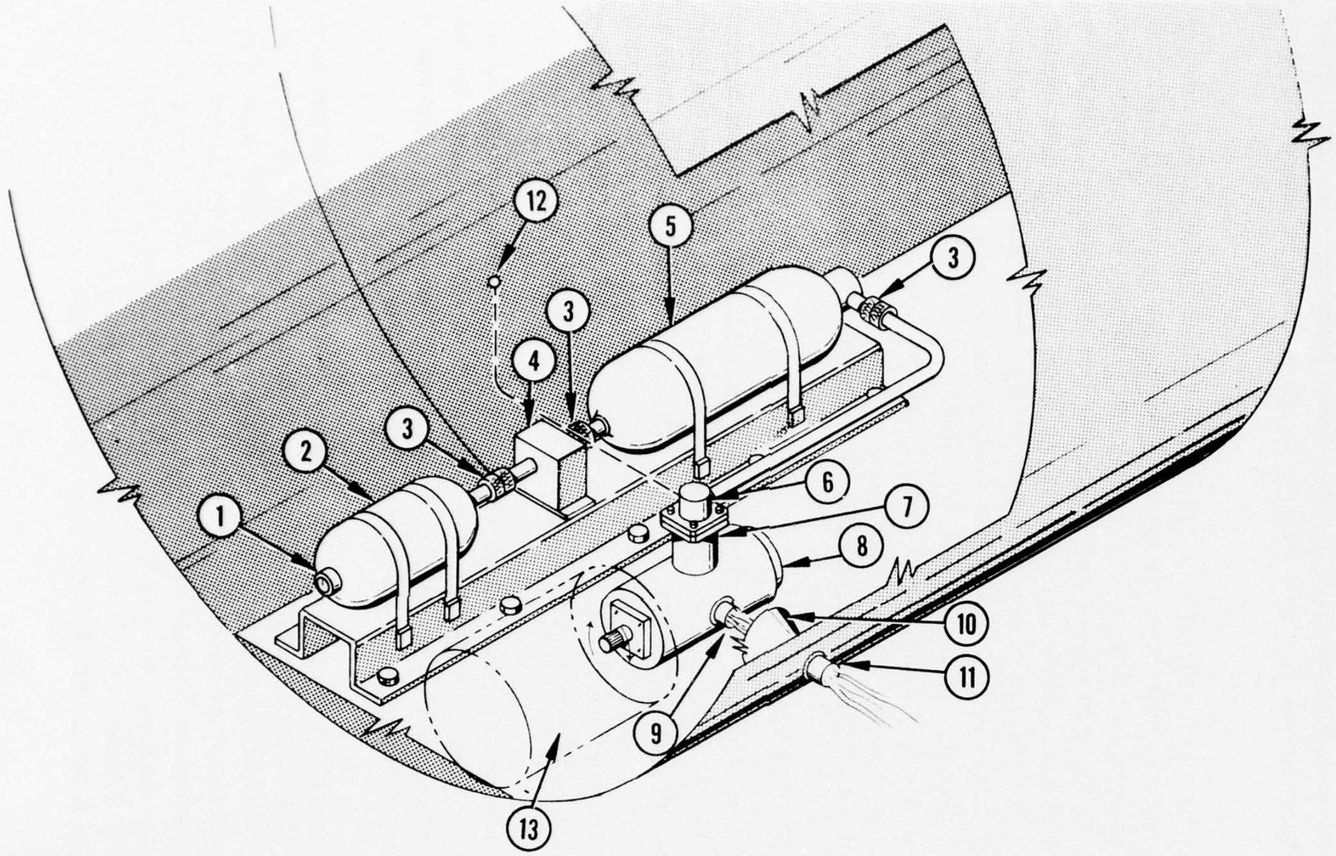
Therefore, the primary purpose of this contract (and this report) has been to screen potential rotary vane hot gas motor design concepts, select the most favorable design approach, and conduct detailed design and analysis studies to develop a set of detailed manufacturing drawings for the hot gas motor.

HYDRAZINE FUELED APU STARTER CONCEPT

The hydrazine fueled APU starter concept utilizes demonstrated state-of-the-art monopropellant hydrazine technology to provide multiple start capability for aircraft APU's at ambient temperatures ranging from -65 to +130°F. The basic hydrazine fueled APU starter concept is shown in the artist's rendering of Figure 1 and as a simplified schematic in the Figure 1A insert. Referring to Figure 1A, the major system components are a pressurized source of monopropellant hydrazine based fuel, control valves, a gas generator, and the hot gas motor. The principle of operation is as follows:

1) When an APU start is required, the gas control valve is opened. This applies regulated nitrogen pressure on the fuel supply.
2) With the fuel tank pressurized, the fuel control valve is opened. This allows pressure regulated fuel flow to the gas generator.
3) The liquid fuel is catalytically decomposed to hot gas in the gas generator.
4) The high pressure hot gas is then utilized to power the hot gas motor. The hot gas motor accelerates the APU to self-sustaining speed.
5) A propellant control system terminates starter system operation when the APU start has been accomplished (an overriding clutch prevents motoring of the starter motor when the APU is operating).

The significant mechanical details of the system are shown in the artist's rendering of Figure 1. High pressure nitrogen would be contained in a removable pressure vessel 2. The gas control valve/pressure regulator 4 would be permanently installed in the aircraft. The hydrazine based fuel supply would be contained in a removable positive expulsion pressure vessel 5. Nitrogen and fuel tankage capacity would be sufficient for at least 20 full-power, full-duration APU start cycles at worst-case -65°F operating conditions.



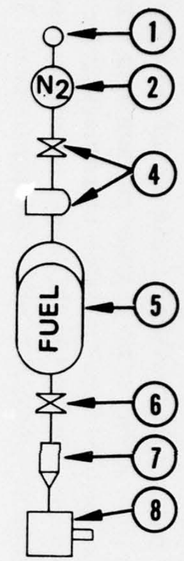


Figure 1A

1 PRESSURE GAUGE
2 NITROGEN TANK
3 QUICK DISCONNECT (3 PL)
4 NITROGEN CONTROL SYSTEM
5 FUEL TANK

6 FUEL CONTROL VALVE
7 GAS GENERATOR
8 HOT GAS MOTOR
9 HOT GAS MOTOR EXHAUST

10 EJECTOR
11 OVERBOARD EXHAUST PORT
12 CONTROL LANYARD
13 APU

Figure 1. Hydrazine APU Starter Concept

Aircraft maintenance personnel would monitor the operational readiness of the system by reading the pressure gauge (1) on the nitrogen tank. When the no-go lower pressure limit is indicated, the nitrogen tank and the fuel tank would be removed from the system by unstrapping the tank mounts and actuating the leakproof quick disconnect fittings (3). Precharged replacement tankage would then be installed in the system to support subsequent APU start requirements. This modular approach for the pressurant and fuel tankage eliminates exposure of the maintenance crew to both working fluids and eliminates special training and ground support equipment for recharging the system on the flight line. Pressurant and fuel tank refilling operations would be done at the depot level.

The APU spin-up is initiated by opening the nitrogen control valve (4) and the fuel control valve (6). These valves would be manually operated valves, actuated by pulling the lanyard (12). With these valves actuated open, high pressure fuel flows from the fuel tank (5) through the fuel control valve (6) to the gas generator (7). The fuel control valve and the gas generator are permanently installed on the hot gas motor (8) which in turn is mounted on the starter pad of the APU (13). Low pressure warm gas leaves the hot gas motor through the exhaust port (9). The residual energy of the exhaust gas would be used to power an ejector (10). The ejector would entrain air from the APU cavity in the aircraft. This entrained air would be drawn over the exterior surfaces of the hot gas motor through a shroud that is not shown. The entrained air would cool the exterior surfaces of the hot gas motor and remove any hot gas leakage that may occur through the motor shaft seals. The entrained air would also reduce the exhaust gas temperature at the overboard exhaust port (11).

COMPONENT DEVELOPMENT STATUS

Three of the four major system components required for the hydrazine fueled APU starter concept are considered to be available as of the shelf or start-of-the-art components. These are the items required for the pressurized source of hydrazine based fuel (tankage, fill valves, quick disconnects, etc.), the control valves, and the gas generator. (The technology to build and operate a gas generator with the proposed hydrazine fuel blend has been demonstrated at -65 to +130^{o}F operating conditions under a previous Wright Patterson AFB Contract F33615-75-C-2027.)

The only major system component that is not available is the hot gas motor. Extensive supplier and literature surveys have been conducted to identify a suitable off-the-shelf hot gas motor for this application. The results of these surveys were negative. Therefore, RRC has undertaken the task of designing the hot gas motor, as discussed in the following sections of this report.

The primary intent of this program is to provide a detailed design and analysis of the hot gas motor portion of the starter system to allow fabrication and testing of this motor concept on subsequent programs. These program goals and requirements have been completed, and ensuing sections of this report define the design and operation of the hot gas motor. A complete set of detailed motor component drawings is presented in Section V; and Section VI presents data relating to the projected performance of the entire starter system. It should be noted that although the motor design resultant from these program efforts is intended to operate with hydrazine hot gas decomposition products, the design is that of a true "hot gas motor", and can be made to operate

with any high pressure/high temperature gas source. This "multifluid" operational ability should prove very beneficial in other nonhydrazine applications where rotary shaft power is to be derived from a hot gas source.

BACKGROUND INFORMATION

In view of these fundamental problems with the current starter systems, the following preliminary specifications were generated to establish the design and selection criteria for alternate starter system concepts:

a. *Performance requirements* – Figure 2 represents the torque-speed characteristics of an advanced APU which is felt to possess the most stringent starting requirements. The starter system must be designed for these requirements.

b. *Operating temperature range* – These temperatures range from -65°F to +130°F.

c. *Multiple start cycle capability* – The hot gas APU starter system should be capable of providing 20 APU starting cycles at -65°F with no refurbishment or between-cycle maintenance.

d. *Operational orientation* – Future applications of the resultant system should be capable of zero or negative gravity application and omnidirectional operation; hence, liquid propellant systems must incorporate a means of positive propellant expulsion.

e. *Operational life* – The APU must be capable of 1,000 operational cycles with only minor maintenance (i.e., replacement of propellant/expulsion tanks after depletion of the 20-start cycle propellant load).

With careful consideration being given to the current pneumatic-hydraulic starter system shortcomings and the design specification required for the hot gas APU starter system, a detailed evaluation was conducted and the results of these analyses were presented in RRC Proposal 76-P-764. These analyses evaluated the following types of hot gas motor concepts:

Rotating gear	Piston/crankshaft
Wankel expander	Rotary vane
Piston/swashplate	Helical screw

After establishment of a quantitative ranking system for each of the various expander types, the rotary vane hot gas motor was selected as the optimum candidate for this application. A schematic representation of this motor concept is presented in Figure 3, and the operational fundamentals of this unit are described as follows.

> The hot gas rotary vane motor shown in Figure 3 consists of a cylindrical starter (length-to-diameter ratio of approximately 1.0) which contains an eccentrically mounted rotor. This rotor incorporates radial slots containing sliding vanes; and the vanes are forced against the stator walls by centrifugal force, pressure force, and minor mechanical spring forces for starting purposes. With reference to Figure 3, the volume between the vertical vane and the No. 1 vane forms a pocket for the admission of hot gas via the inlet.

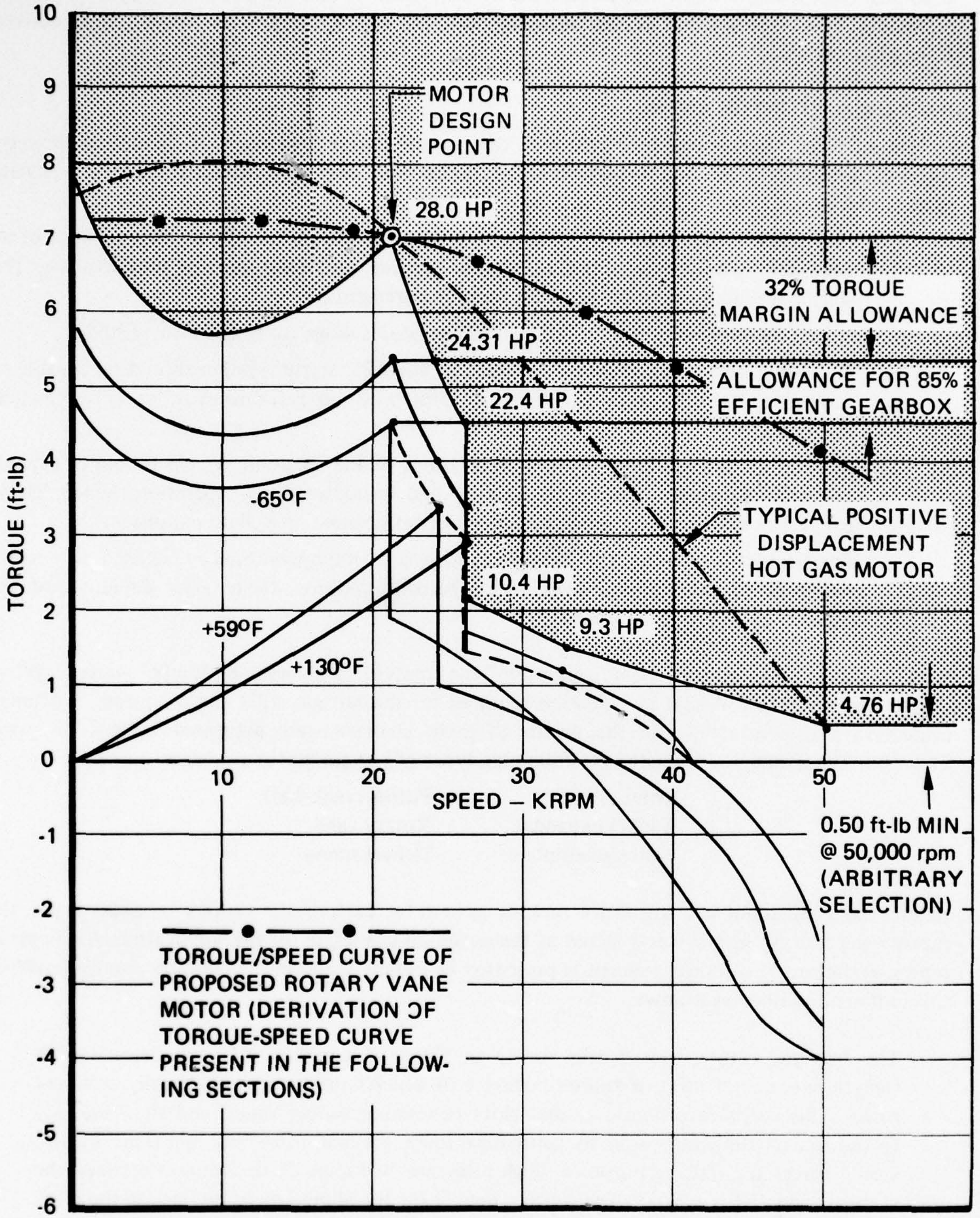


Figure 2. Starter System Envelope

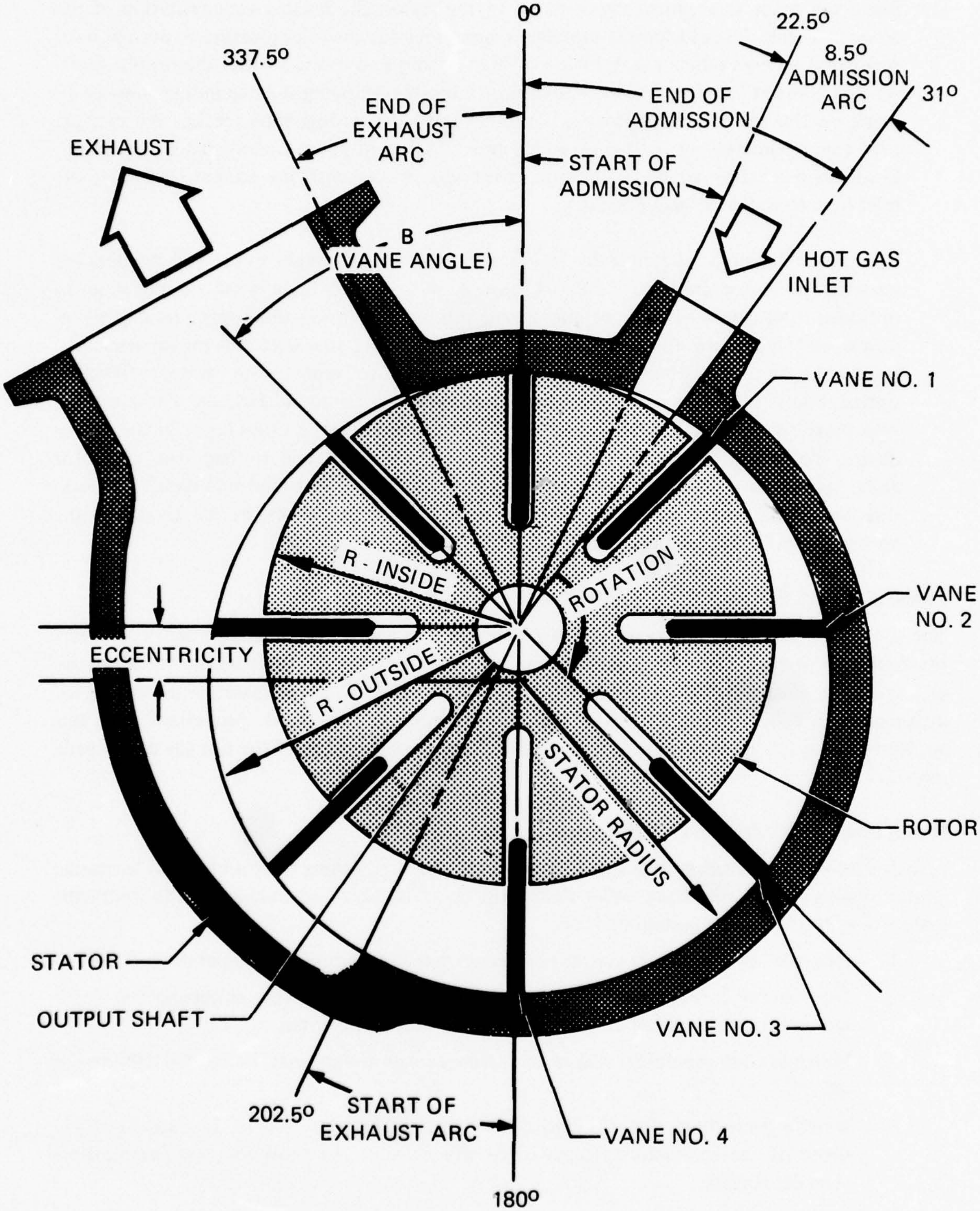


Figure 3. Rotary Vane Motor

Since the rotor is eccentrically situated in the stator, the leading vane (rotation of the rotor in Figure 3 is clockwise) provides a larger area for the inlet pressure to act upon (as compared to the vertical vane); hence, a force or torque is created about the output shaft. As this "pocket" rotates, the pocket volume increases, allowing the expanding gases to do work on the shaft. This expansion continues until the leading vane reaches the exhaust port (approximately at 7:00), at which point the spent gases are exhausted overboard. Continuing rotation of the rotor purges the gas pocket until the pocket intercepts the inlet port to accept a fresh gas charge.

The motor depicted schematically in Figure 3 is shown with eight vanes, and the detailed analyses presented in RRC 76-P-764 have shown this to be a good compromise to optimize total starter system weight. Fewer vanes result in less than optimum expansion ratios, and increasing the number of vanes significantly increases the motor frictional losses. As becomes obvious in later sections of this report, the motor efficiency optimization results in a compromise between vane friction and leakage. These are the two most thermodynamically important factors that must be considered in the motor design. To minimize leakage between the adjacent pockets and spillage over the rotor ends, the vanes must be forced tightly against the stator walls and end caps. This is in direct contrast to the design problem of reducing friction losses, as the tighter fitting vanes present higher friction loads.

PRIMARY GAS SOURCE

The previously described rotary vane hot gas motor serves as a system component to convert the enthalpy of high pressure, high temperature gases into useful shaft work; but an entire starter system must provide a hot gas source to power the motor. As discussed in detail in RRC document 76-P-764, monopropellant hydrazine provides an ideal propellant for this application and has been selected as the baseline for demonstration of the hot gas rotary vane motor.

Monopropellant Hydrazine Characteristics

A hydrazine-fueled starter system offers the potential of overcoming the problems of hydraulic starter systems while providing other significant benefits. Major advantages of the hydrazine system over the hydraulic system include:

1) Relative insensitivity of starter performance to environmental temperature.
2) Due to the insensitivity of 1) above and existence of catalyst capable of -65°F ignition, true operation at -65°F conditions may be achieved.
3) Multiple start capability with a hydrazine-fueled system may be readily achieved at -65°F.
4) Weight projections for the hydrazine-fueled systems are 20 to 30 percent below those of the hydraulic systems while still providing the low temperature multiple start capability.

The advantages offered by a hydrazine-fueled APU starter system are such that development work to demonstrate its feasibility is warranted. Such a system represents a logical replacement of existing systems in order to improve the operational capability and flexibility of current and future military aircraft. The major development problems which RRC anticipates in development of the hydrazine starter and the proposed approach to the solutions of these problems are discussed in the following sections.

IGNITION AT -65°F – Obtaining reliable and repeatable ignition characteristics at -65°F conditions with a catalytic gas generator requires detail attention be given to the gas generator design and start sequence. Testing conducted by RRC on Contract F33615-75-C-2027 and on other in-house work has shown that -65°F ignition may be reliably obtained.

On Contract F33615-75-C-2027, RRC developed an eight-cup gas generator for a hydrazine-fueled aircraft cartridge starter. The gas generator requirements for the APU starter are such that one of the cups from the aforementioned program is optimum for use. This allows the selection and use of a gas generator design approach which has demonstrated -65°F ignition capability and which has appreciable development history behind it. This gas generator uses an injector element which penetrates into the catalyst bed and injects the propellant radially outward. Momentum of the injected propellant is controlled to allow rapid spreading into the catalyst bed but is limited to prevent excessive catalyst loss rates. This injector design approach has proven effective in rapidly wetting the catalyst to provide -65°F ignition.

The selection of the propellant mixture must consider the viscosity at low temperature. If a mixture is selected which has a freezing point very close to -65°F, the mixture will be very viscous and will not rapidly disperse in the catalyst bed and wet the catalyst. The propellant blend selected by RRC has a measured freezing point of -90°F and a thawing temperature of -85°F, providing good margin over the -65°F requirement. Viscosity measurements of the blend show adequate properties at -65°F.

CATALYST POISONING – Rocket Research Company currently supplies a catalytic gas generator to Sundstrand Corporation for use on the Space Shuttle hydraulic APU. Tests of this system have shown that leakage of hydraulic oil into the gas generator bed can result in permanent damage to the catalyst bed. This deactivation can occur as the result of direct injection of oil into a hot catalyst bed or from oil hitting a hot surface, vaporizing and entering the catalyst bed. It is, therefore, necessary to provide leak-tight oil seals between any oil cavity and the gas generator to prevent catalyst deactivation. Rocket Research Company believes a better approach is to arrive at a design concept which does not employ any oil and has baselined with such a design approach.

SYSTEM MAINTAINABILITY – In application, the hydrazine-fueled APU starter will be installed in aircraft and serviced by military personnel. To minimize system in-use cost and servicing by personnel, system maintainability must be a strong consideration in arriving at the baseline system design approach.

Rocket Research Company believes that maintainability requirements are minimized by arriving at a system design approach which utilizes system design techniques and components which have a high history of prior use and long time applications between failures. It is a goal of the system design to select a system approach and components which have 1,000 start minimum capability between maintenance cycles. The only maintenance on the system between the 1,000 starts will be replacement of propellant and pressurant tanks at the end of each 20-start interval. Both tanks have been equipped with quick disconnect fittings to facilitate removal and replacement in the aircraft by military personnel.

EXHAUST GAS PRODUCTS – The exhaust gas products from the gas generator consist of nitrogen, hydrogen, ammonia and water. The ammonia represents a noxious material which has established concentration limits to which personnel may be exposed. The hydrogen and ammonia are flammable if concentrated in proper proportions.

For the proposed application, the starter requires approximately 1.2 lbm of hydrazine per -65°F start. This relatively small quantity of fuel greatly minimizes toxicity and/or flammability problems during operation. For each start, the following quantities of decomposition gases will result:

Ammonia	–	0.24 lbm
Hydrogen	–	0.046 lbm
Nitrogen	–	0.546 lbm
Water	–	0.372 lbm

As noted above, the amount of hydrogen is sufficiently small to present no significant flammability problem on start and will dissipate rapidly by molecular diffusion. Similarly, the amount of ammonia is sufficiently small to cause no toxicity problem. The total amount of ammonia contained in a 10-foot cube would result in a concentration of only 1,500 ppm and would rapidly dissipate without danger to personnel.

As a further means of reducing the flammability, toxicity, and temperature of the overboard exhaust products, RRC recommends that the hot gas motor exhaust ducting be configured as an ejector to entrain ambient air from the APU equipment bay. The ejector shroud would include a sheet metal enclosure around the hot gas motor; ambient air pulled through this shroud would augment the cooling of the motor and entrain any hot gas leakage from the motor.

HYDRAZINE HANDLING – Hydrazine is a toxic compound, and handling must be limited to personnel trained in its use. Additionally, it must not be exposed to the air. To limit the personnel who must refill tankage, the RRC system design incorporates a removable fuel tank with zero leakage quick disconnects on each end of the tank. In this manner, the tank may be removed from the aircraft without exposure to hydrazine and/or its fumes by maintenance personnel. The tank would then be refilled at a depot using personnel trained in handling of hydrazine. At the depot, necessary precautions for handling of hydrazine may be more easily implemented than by maintenance personnel working on the aircraft.

Hydrazine is currently being applied to use on several military aircraft, and out of these applications will evolve design approaches and handling techniques which are optimum for military personnel.

HOT GAS MOTOR LIFE – To provide a system with low life cycle costs, it is necessary that the hot gas motor have long-life capability with a goal of at least 1,000 starts between refurbishment. The total run time for 1,000 starts is not excessively high, being 2 to 4 hours. The wear characteristics of piece parts, however, are a strong function of the temperature environment, temperature cycling, and the decomposition gas environment.

The exhaust gas products described in "Exhaust Gas Products" represent constitutents that are very familiar to RRC, and the resultant hot gas motor design incorporates materials consistent with the 1,000-cycle operational life requirement.

Propellant Selection

The ideal fuel for monopropellant hydrazine use in the APU starter is anhydrous hydrazine due to its extensive use in past and present space programs involving long-life and long-term storage. Unfortunately, the freezing point of the anhydrous hydrazine is approximately +35°F and is inconsistent with the requirement for system operation over a temperature range of -65° to +130°F.

Neat hydrazine could be considered if sufficient electrical power were available to power system heaters to prevent fuel freezing at low system soak temperatures. However, the lack of power availability, the undesirable complication of system heaters, and the reduced system reliability eliminate the feasibility of this approach.

There are a number of additives and combinations of additives that may be used to depress the freezing point of anhydrous hydrazine. These additives are identified and discussed in the following paragraphs.

HYDRAZINE ADDITIVES – Candidate freezing point depressant additives for hydrazine include water, ammonia, hydrazinium nitrate (HN), monomethyl hydrazine (MMH), ammonium thiocyanate, hydrogen cyanide, and hydrazinium azide.

One of the preliminary considerations in the selection of additives to reduce the freezing point is the type of decomposition chamber to be employed in the system. Since the hydrazine-fueled APU starter will require a spontaneous type catalytic reactor with long-life and multiple restart capability, any carbon containing additives must be eliminated from consideration as a viable candidate since additives in this family will deposit carbon on the active sites of the catalyst and reduce the effective activity of the catalyst below that required for repeated restart capability. This reduces the candidate additives to water, ammonia, and hydrazinium nitrate. The azide propellants offer no advantages over nitrated propellant. The safety characteristics are inferior, and gas generator tests indicate an order of magnitude increase in catalyst loss rate over the nitrate propellants.

A second consideration in the selection of additives is their effect on the energy content of the resultant fuel mixture. Water and ammonia will reduce the energy content of the blend, and hydrazinium nitrate will increase the energy content. Rocket Research Company has had several previous contracts involving the evaluation and test of ternary and binary mixtures of hydrazine, hydrazinium nitrate, water and ammonia which provide a large base of engineering data from which a final selection of the fuel blend for the APU starter program may be made. These include the following programs and fuel blend studies:

a. NASA Contract NAS7-372, in which hydrazinium nitrate, hydrazine and water blends were tested having freezing points of +20, 0, and -20°F while retaining the same performance as neat hydrazine. Excellent performance was obtained in 5-lbf engine tests.

b. Air Force Contracts AF04(611)-11376 and F04611-67-C-0058, in which hydrazine, water and ammonia blends were characterized from performance, compatibility, and physical property aspects. Gas generator tests were conducted with a wide range of blends to obtain experimental data and overall operation with Shell 405 and the blends.

c. Shell Development Contract SDWO 84762 under Air Force Contract F04611-67-C-0023, in which engine tests were conducted with hydrazine/hydrazinium nitrate propellant.

d. LMSC Contract CT 10A15COM, in which experimental tests were conducted on 8- and 75-lbf engines with a 24% hydrazinium nitrate/76% hydrazine propellant blend. The program also included extensive materials compatibility and safety characterization of the propellant blend.

e. A classified program in which mixtures of hydrazine/hydrazinium nitrate and water were studied as a replacement for neat hydrazine that provided a low freezing point blend and eliminated the need for heaters required to keep neat hydrazine above the freezing point. This program included both propellant and compatibility tests and engine firing tests.

f. Wright Patterson Air Force Base Contract F33615-75-C-2027, which resulted in the feasibility demonstration of a hydrazine-fueled starter cartridge using hydrazine/hydrazinium nitrate/water propellant blends. Two blends were tested; both had freezing points below -65°F. One was a mixture consisting of 60% hydrazine, 21% hydrazinium nitrate, and 19% water (termed TSF-1); and the second was a mixture of 58% hydrazine, 25% hydrazinium nitrate, and 17% water (termed TSF-2). The TSF-2 blend is slightly more energetic than the TSF-1 blend, and both have energy content and flame temperature similar to anhydrous hydrazine.

BINARY PROPELLANT MIXTURES – Binary mixtures of hydrazine and water, ammonia, or hydrazinium nitrate can be evaluated in gross terms for the application of interest, as follows:

1) *Hydrazine/Water* – A -65°F freezing point is obtainable with reasonable fuel mix energy content. The energy content is approximately 75% of that obtainable from anhydrous hydrazine.

2) *Hydrazine/Ammonia* – A -65°F freezing point requires approximately 64% ammonia by weight; the energy content of the resultant mixture is not adequate for this application. Additionally, the high vapor pressure of an ammonia additive would increase the

complexity of fuel mix operations; therefore, ammonia is not considered as a viable candidate for a freezing point depressant for the application proposed herein.

3) *Hydrazine/Hydrazinium Nitrate* – The maximum freezing point depression obtainable with this mixture is $0^{o}F$ when consideration is given to selecting a mixture which is not in a shock-sensitive range. Therefore, a binary mixture of hydrazine/hydrazinium nitrate cannot be considered for the application described herein.

TERNARY PROPELLANT MIXTURES – Hydrazine can be combined with various percentages of water and hydrazinium nitrate as a ternary blend to satisfy the $-65^{o}F$ freezing point requirement. Additionally, the resultant ternary mixes have a greater energy content than the hydrazine-water mix previously discussed and are stable compounds which are not shock sensitive. By proper selection of the propellant mixture, blends may be formulated which have freezing points less than $-65^{o}F$ and which have gas temperatures and energy content similar to anhydrous hydrazine.

PROPELLANT SELECTION – The above review of the additives available and a consideration of the long-life requirement for the catalytic gas generator, with multiple restart capability, have resulted in the selection of water, or a combination of hydrazine nitrate ($N_2H_5NO_3$) and water, as the preferred freezing point depressant additives for the APU starter application.

Figure 4 depicts the freezing point characteristics of binary mixtures of water and anhydrous hydrazine as a function of the percentage by weight of hydrazine in the mix. The required $-65^{o}F$ freezing point may be obtained in fuel mixtures containing 32, 57, or 68 percent hydrazine. A hydrazine/water mixture containing 68 percent hydrazine would maximize the energy content of the fuel mix.

Freezing point depression to $-65^{o}F$ can be obtained with any ternary mixture of hydrazine, hydrazine nitrate, and water within the boundary established by the dashed envelope of Figures 5 and 6 (i.e., outside the shock-sensitive boundary). The energy content of the resultant mixture increases as the mixture becomes richer in hydrazine or hydrazine nitrate content as noted by the superimposed exhaust gas isotherms. Figure 5 presents isotherms for 40% ammonia dissociation, and Figure 6 presents data for 60% dissociation. The most energetic mixtures lie in a regime that is classified as detonable by the card gap test method.

The liquid bulk density of the candidate binary and ternary fuel mixes can be determined from the data shown in Figure 7. It will be noted that the ternary mixes of interest for the APU starter are significantly denser (approximately 10%) than the binary hydrazine/water mixtures.

The relatively high bulk density of the ternary mixes and the energy content of the resultant exhaust products will combine to yield the minimum required fuel storage volume for a given APU starter operating cycle.

The temperature and the composition of the exhaust gas generated by the decomposition of hydrazine-based fuels is a strong function of the chemical composition of the fuel mix, temperature of the fuel supplied to the gas generator, and certain physical design variables in the decomposition chamber.

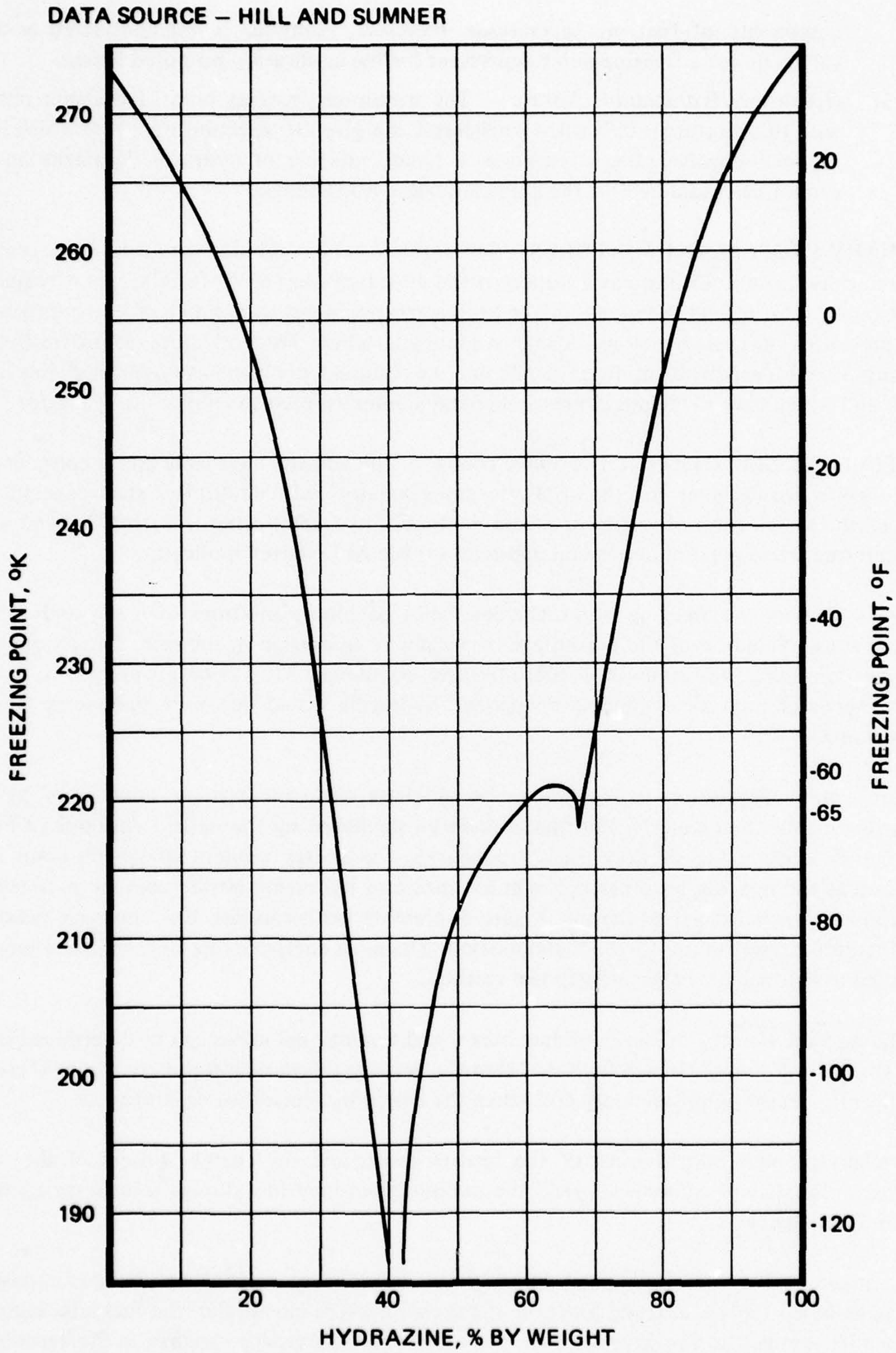


Figure 4. Freezing Point of Hydrazine Water Mixtures

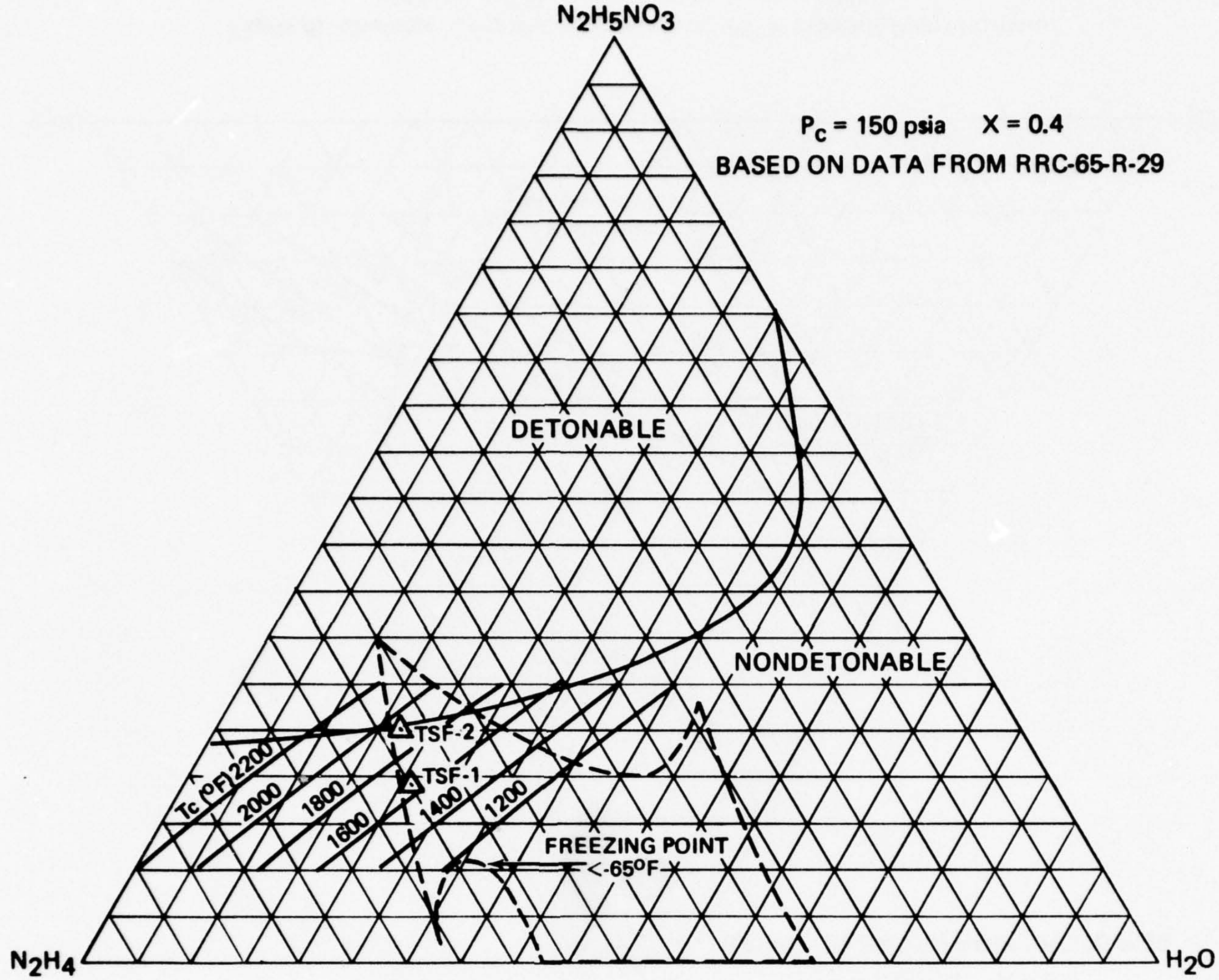


Figure 5. Chamber Temperature Profile and -65°F Freezing Point Isotherm of Hydrazine/Hydrazinium Nitrate/Water Mixtures

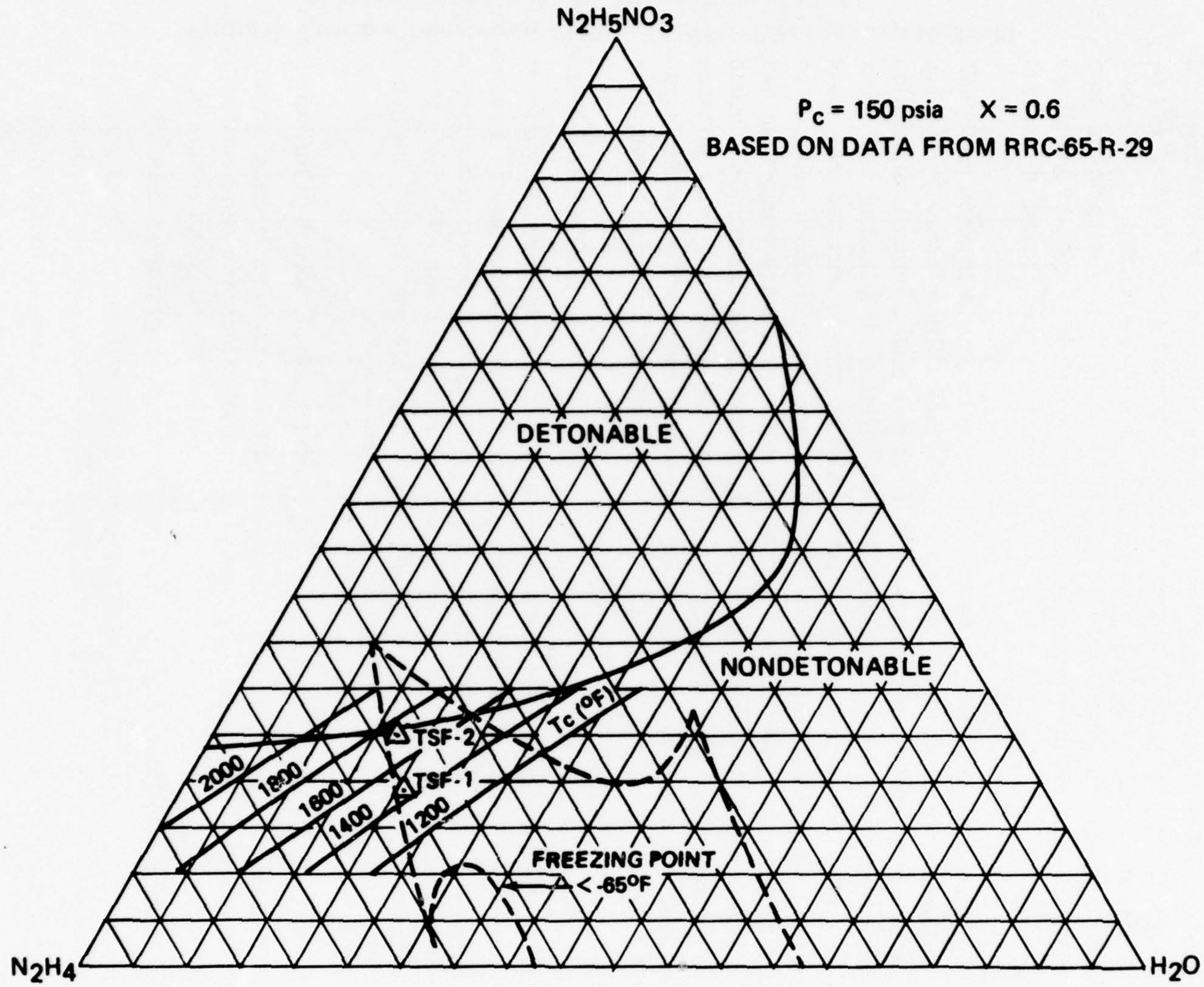


Figure 6. Chamber Temperature Profile and -65°F Freezing Point Isotherm of Hydrazine/Hydrazinium Nitrate/Water Mixtures

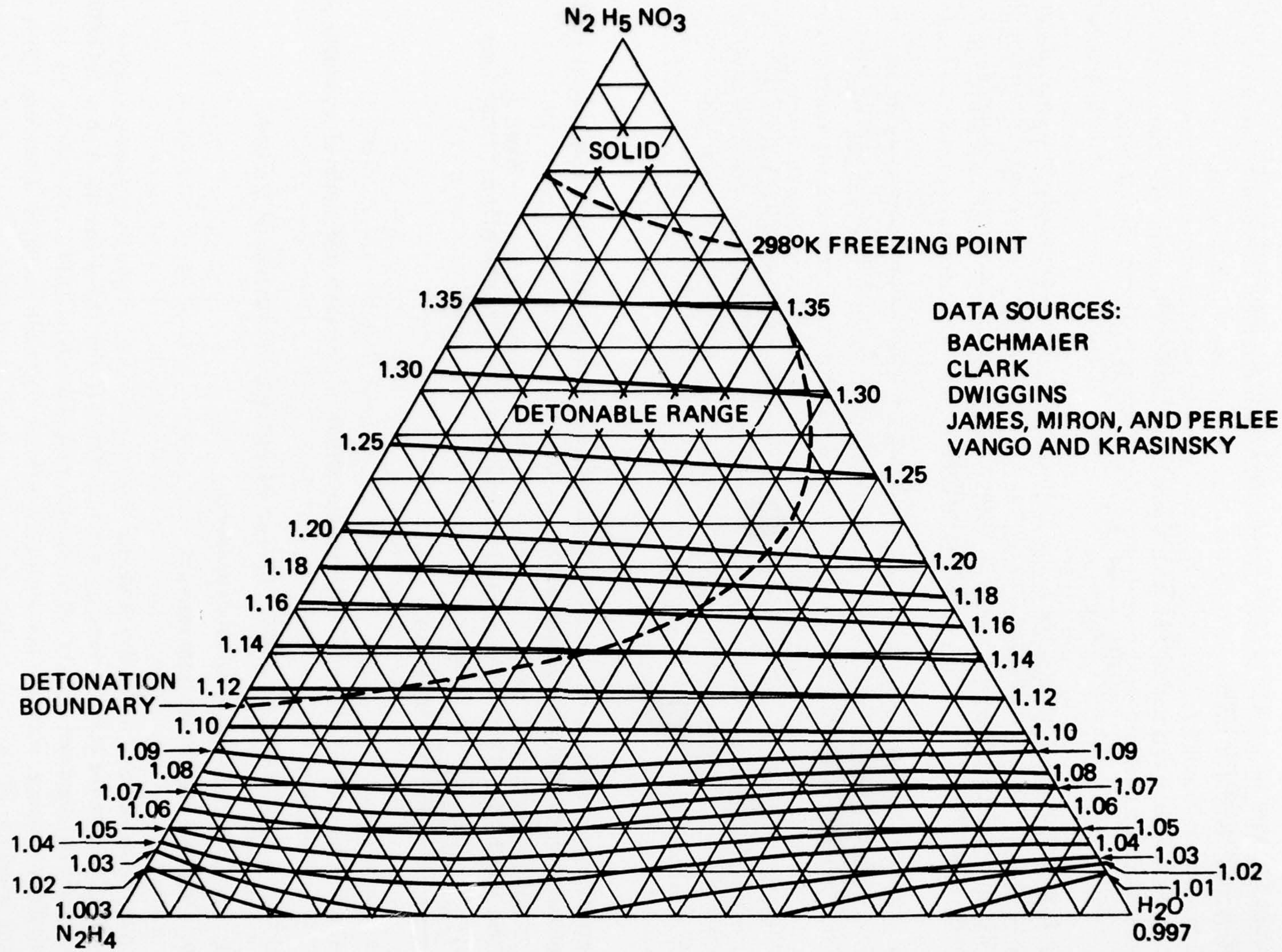


Figure 7. Density of Hydrazine/Hydrazinium Nitrate/Water Ternary Mixtures, g/cm^3 at (298°K) 77°F

Hydrazine fuel may be considered to be decomposed in the gas generator reactor according to the following consecutive reactions:

$$3N_2H_4 \longrightarrow 4NH_3 + N_2 + 144{,}300 \text{ Btu} \qquad (1)$$

$$4NH_3 \xrightarrow[\text{cat}]{} 2N_2 + 6H_2 - 79{,}200 \text{ Btu} \qquad (2)$$

In the first step of the reaction model, the hydrazine is broken catalytically into ammonia and nitrogen. In the second step, the ammonia formed is dissociated into nitrogen and hydrogen. In the first step, the exhaust products would be slightly toxic due to the presence of ammonia and relatively nonflammable due to the absence of hydrogen.

In the second step, which is exothermic, the exhaust gas temperature decreases as the ammonia dissociates into nitrogen and hydrogen, effectively reducing the toxicity of the exhaust products and increasing their flammability due to the presence of hydrogen.

Basically, the control of the flow variables and the geometry of the gas generator control the degree of completion of the second step of the reaction process for a neat hydrazine fueled gas generator. This provides the designer a means of controlling the exhaust gas temperature and composition of the exhaust products. Equations (1) and (2) may be combined as follows for calculation purposes:

where X = fraction of NH_3 dissociated

The generalized reaction equation for the hydrazine/hydrazinium nitrate/water propellant blend may be expressed by the following equation:

$$N_2H_4 + hn\ N_2H_5NO_3 + W\ H_2O \longrightarrow (3\ hn + W)\ H_2O + \frac{(1 - x)(4 - hn)}{3} NH_3 + \frac{X(4 - hn)}{2} H_2 \qquad (3)$$

$$+ \frac{2(2X + 1) + hn(10 - x)}{6} N_2 + \Delta Q_r$$

where:

hn	=	number of moles of hydrazinium nitrate in reactants per mole of hydrazine in reactants
W	=	number of moles of water in reactants per mole of hydrazine in reactants
X	=	fraction of dissociation of ammonia
ΔQ_r	=	net heat release from reaction.

The ternary mixes selected for further study for this application are shown by triangular symbols on Figures 5 and 6 and the compositions are shown in Table 1. The TSF-2 mix lies within the -65°F freezing point envelope and slightly below the detonable boundary. TSF-1 is also within the -65°F freezing point envelope, with additional margin below the detonable boundary. Therefore, TSF-1 is the least energetic of the two ternary mixes but has improved safety margin. Both of these propellant blends have been mixed and tested as a part of the Wright Patterson hydrazine starter cartridge program recently completed by RRC.

Table 1. Composition of Candidate APU Starter Fuels

Fuel Mix Identifier	Composition % by Weight		
	N_2H_4	$N_2H_5NO_3$	H_2O
TSF-1	60	21	19
TSF-2	58	25	17
TSF-3	68	–	32

For the fuel mixes of interest, equation (3) may be utilized and calculations made of all of the properties of the resultant exhaust gas for a meaningful range of ammonia dissociation (X) over a fuel supply temperature of -65 to +160°F. Table 2 summarizes the thermochemical characterization of the candidate fuel mixes for study. Table 3 summarizes the exhaust gas composition of the candidate propellant blends as a function of ammonia dissociation.

Tests conducted by RRC on water/hydrazine mixtures indicate that no ammonia dissociation is obtained below 1,000°F exhaust gas temperature. For the selected water/hydrazine blend, ammonia dissociation values of zero to 20 percent are expected. For the nitrated propellant blends, tests on the hydrazine cartridge starter program have resulted in ammonia dissociation values of 0 to 60% over environmental temperature extremes of -65 to +160°F.

To summarize the foregoing, the characteristics of the candidate fuel mixtures can be compared to the unique requirements associated with the APU starter application. These considerations are:

1) There is a basic requirement to package the fuel in a minimum storage volume envelope and to minimize overall system weight. TSF-2 has the highest energy density, followed by TSF-1 and TSF-3.

2) There is a desire to minimize the amount of ammonia and hydrogen in the starter exhaust products.

Ammonia-rich exhaust products will have a toxicity roughly equivalent to that of existing solid propellant cartridge starter exhaust products. A review of the exhaust products generated by the current solid propellant cartridge indicates that these products are more toxic (carbon monoxide, hydrogen cyanide, and ammonia) than the exhaust from a hydrazine-fueled starter with ammonia-rich exhaust (TSF-3). The flammability of an ammonia-rich exhaust is not considered to be a problem.

Hydrogen-rich exhaust products will be no more flammable than the existing solid propellant cartridges. A hydrogen-rich exhaust would be the most flammable. The flammability of the existing cartridge starter exhaust products is roughly equivalent to a hydrogen-rich hydrazine exhaust (TSF-1 or TSF-2).

Table 2. Thermochemical Performance Characteristics

Fuel Mix	Composition % by Weight			NH_3 Dissociation X	Fuel Supply Temp. °F (T_f)	Gas Temp. °F (T_c)	Molecular Weight ($\bar{M}_c$)	Ratio of Specific Heat Capacities γ_c
	N_2H_4	H_2O	$N_2H_5NO_3$					
TSF-1	60	19	21	0.4	-65	1,594	16.318	1.2486
					+77	1,767	16.318	1.2414
					+160	1,871	16.318	1.2375
				0.6	-65	1,401	15.111	1.2808
					+77	1,576	15.111	1.2723
					+160	1,684	15.111	1.2677
TSF-2	58	17	25	0.4	-65	1,760	16.500	1.2424
					+77	1,929	16.500	1.2361
					+160	2,033	16.500	1.2327
				0.6	-65	1,574	15.310	1.2726
					+77	1,747	15.310	1.2653
					+160	1,853	15.310	1.2612
TSF-3	68	32	–	0.1	-65	980	17.871	1.2426
					+77	1,169	17.871	1.2304
					+160	1,292	17.871	1.2234
				0.2	-65	865	17.011	1.2629
					+77	1,058	17.011	1.2495
					+160	1,182	17.011	1.2418

Table 3. Exhaust Gas Composition of Candidate Propellant Blends

Propellant Blend	Ammonia Dissociation %	Exhaust Gas Composition, % by Volume			
		Nitrogen	Ammonia	Hydrogen	Water
TSF-1	40	23.7	24	24	28.3
	60	25.7	14.8	33.3	26.2
TSF-2	40	24.4	23.4	23.3	28.9
	60	20.2	14.4	32.4	26.9
TSF-3	0	13.3	53.2	0	33.4
	20	16.8	38.5	14.4	30.2

Catalytic Decomposition

Catalysts for the decomposition of hydrazine fall into two classes: those which are spontaneous and initiate decomposition at ambient temperature, and those which must be preheated to varying temperatures before they exhibit sufficient catalytic activity to sustain decomposition.

Catalysts which will not initiate decomposition at ambient temperature typically have to be heated to 500 to 700°F before sufficient activity is obtained to sustain decomposition. These catalysts are typically one or two orders of magnitude less costly than Shell 405 catalyst. Rocket Research Company and other organizations have developed several catalysts which fall in this category. Starting is typically obtained by preheating the bed electrically or with a solid propellant or by coating the catalyst with a solid oxidizer.

Shell 405 catalyst represents the best catalyst available to initiate hydrazine decomposition at ambient temperatures. The catalyst has been thoroughly characterized and developed within the industry. Other catalysts having been developed by Shell, RRC, and others which will initiate decomposition at ambient temperature; but their life characteristics are inferior to Shell 405.

Catalysts other than Shell 405 are available for the decomposition of hydrazine-based propellants. Other catalysts available in the industry are shown in Table 4.

Shell 405 is the catalyst which is currently used in all major space programs involving monopropellant hydrazine thrusters. It is the only spontaneous catalyst which has flight experience and has been extensively characterized and developed for monopropellant applications. The catalyst uses iridium metal deposited on a Reynolds alumina (RA-1) alumina substrate. Because of the high cost of iridium metals and the processing costs, the catalyst is relatively expensive. It should be remembered, however, that for the APU engine starter, the catalyst can be reclaimed after use so that its effective cost is substantially reduced.

Table 4. General Characteristics of Candidate Jet Engine Starter Catalysts

Catalyst	Cost per lbm	Spontaneity	Relative Activity
Shell 405	$4,000	Spontaneous at ambient temperature or below	High
Shell X-B	$300	Low at ambient temperature	Low
Shell X-C	$600	Spontaneous at ambient temperature	Med
Shell X-4	$600	Spontaneous at ambient temperature	Med/High
Shell experimental	~$500	Spontaneous at ambient temperature	High
ESSO 500	~$300	Spontaneous at ambient temperature	High
Pioneer	In range of Shell X-series	Low at at ambient temperature	Low
LCH-101	$100	Nonspontaneous at ambient temperature	Low
LCH-202	$450	Nonspontaneous at ambient temperature	–

On past programs, RRC has utilized other catalysts than Shell 405 and has also utilized combinations of Shell 405 and nonspontaneous catalysts to lower overall cost. While such techniques may be employed at ambient temperature conditions and/or for short life, RRC has demonstrated on the hydrazine starter cartridge program that a catalyst bed of all Shell 405 must be utilized in order to obtain reliable and repeatable ignition at -65°F. Rocket Research Company has therefore selected a catalyst bed of all Shell 405 catalyst to utilize in the gas generator.

Gas Generator Design

During Wright Patterson contract F33615-75-C-2027, RRC demonstrated the feasibility of a hydrazine-fueled cartridge starter. The gas generator developed was capable of reliable -65°F starts and had a higher life capability than the application proposed herein requires. The design characteristics of this gas generator were as follows:

1) Flow rate: 0.5 lbm/sec
2) Chamber pressure: 1,000 psia
3) Operating temperature range: -65 to +160°F
4) Individual burn time per start: 17 seconds
5) Total number of starts: 800 to 1,000

The gas generator developed for the cartridge starter application is shown in Figure 8 prior to assembly of the catalyst bed and in Figure 9 after complete assembly. As shown, the unit consists of eight individual gas generators or cups manifolded to a common fuel inlet. The eight-cup configuration was chosen to allow optimum packaging within the existing solid propellant cartridge breech and also represents a design approach capable of being produced in production at very low cost.

This eight cup gas generator design technology and experience is very applicable to the gas generator required for the APU starting system; hence, it is felt that once the analytical and experimental performance characteristics of the hot gas rotary vane motor are defined, one of the individual "cups" could be scaled up to meet the gas flow requirements. Mounting of the gas generator would be quite near the motor itself to reduce the need for hot gas supply ducts, and a mounting configuration shown in Figure 10 would be typical.

To provide meaningful design data for the hot gas motor, pertinent performance characteristics of the TSF-1 propellant blend measured under Wright Patterson AFB Contract F33615-75-C-2027 have been projected for the flow rates required of the hot gas motor, and this data is summarized in Figure 11.

APU STARTER SYSTEM DESCRIPTION

There are several types of hydrazine feed systems which have been employed to supply propellant to the decomposition chamber. These types of pressurization systems may be classed into the following general categories which are shown schematically in Figure 12:

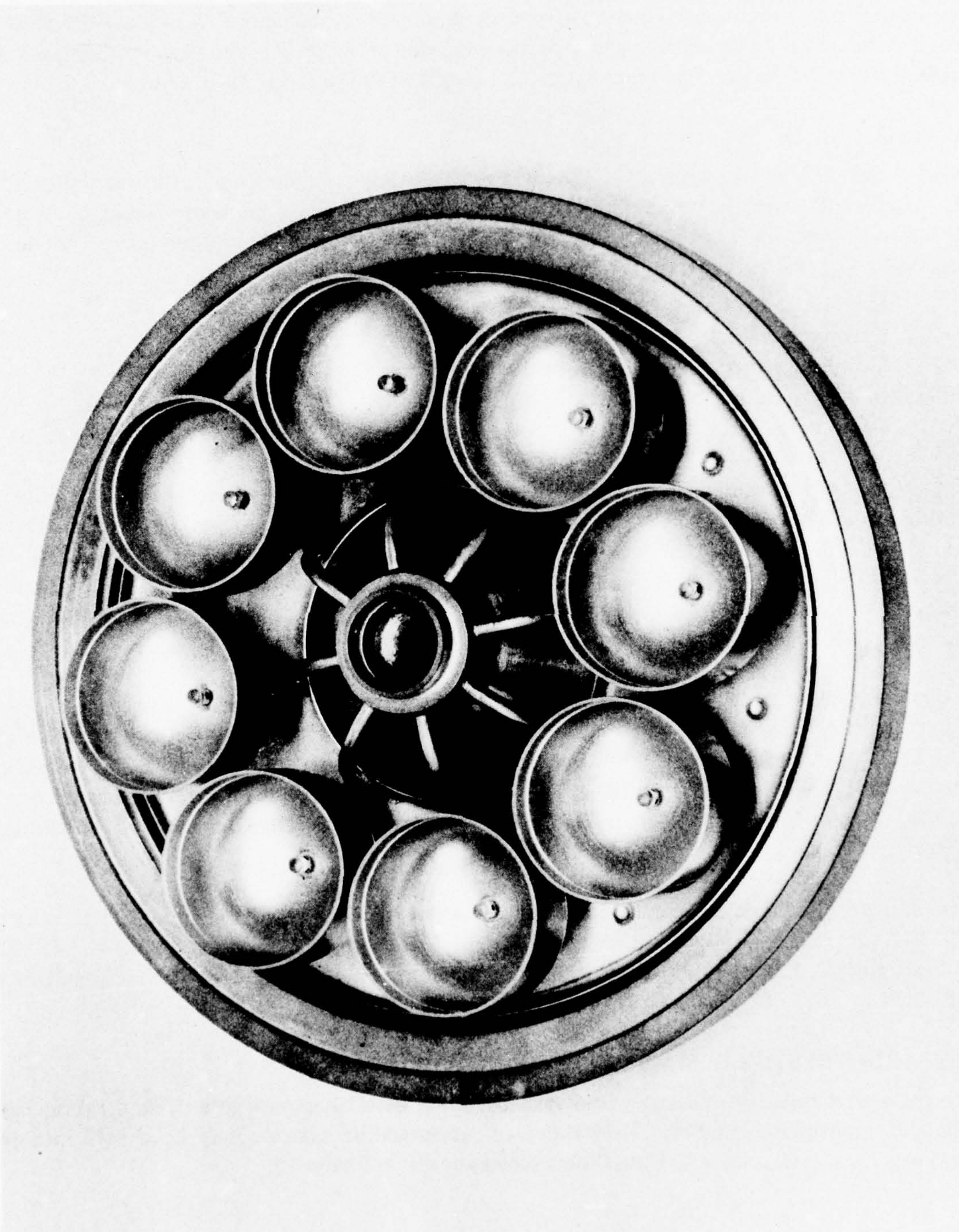


Figure 8. Hydrazine Fueled Starter Cartridge Gas Generator Prior to Catalyst Loading

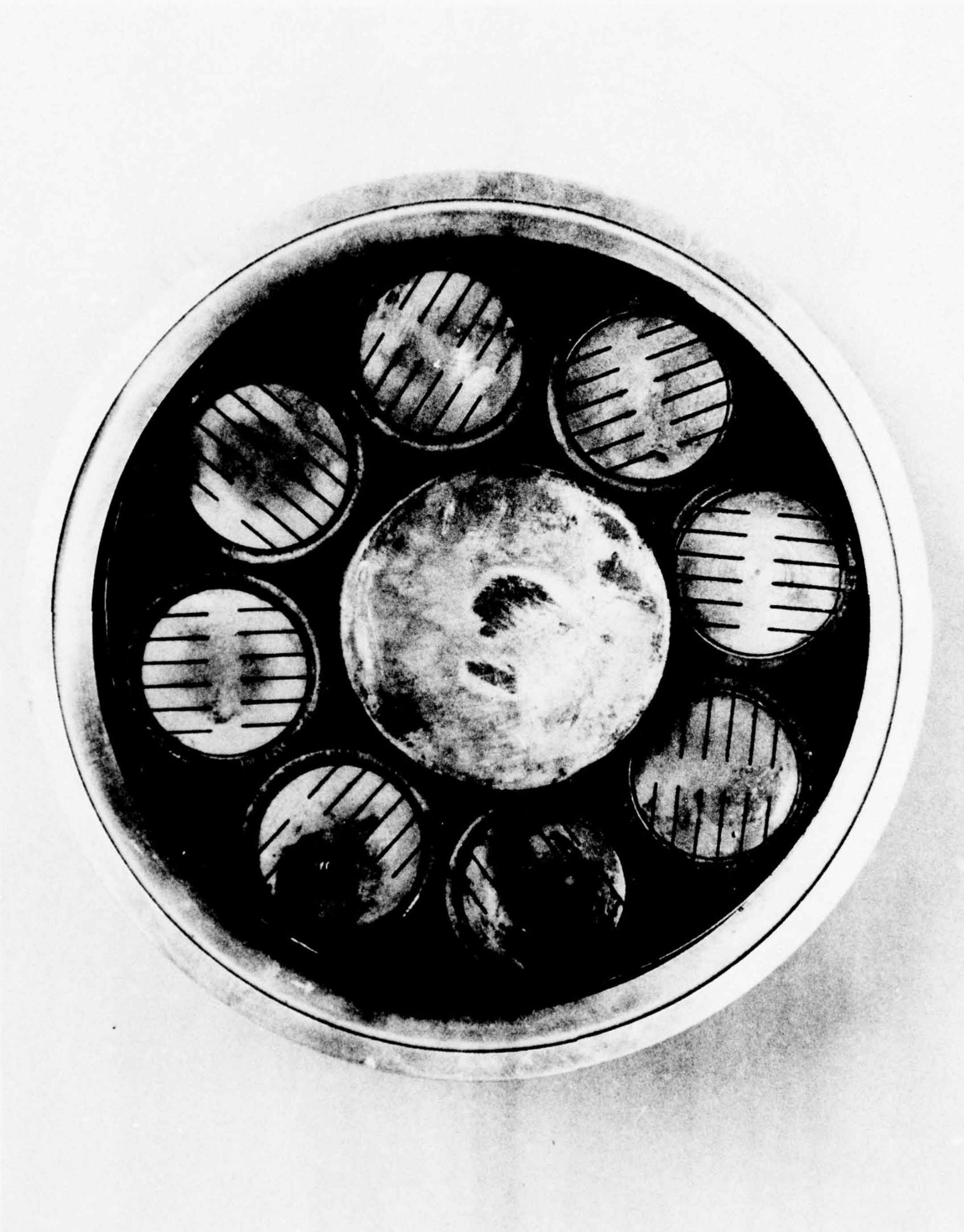


Figure 9. Hydrazine Fueled Starter Cartridge Gas Generator Assembly

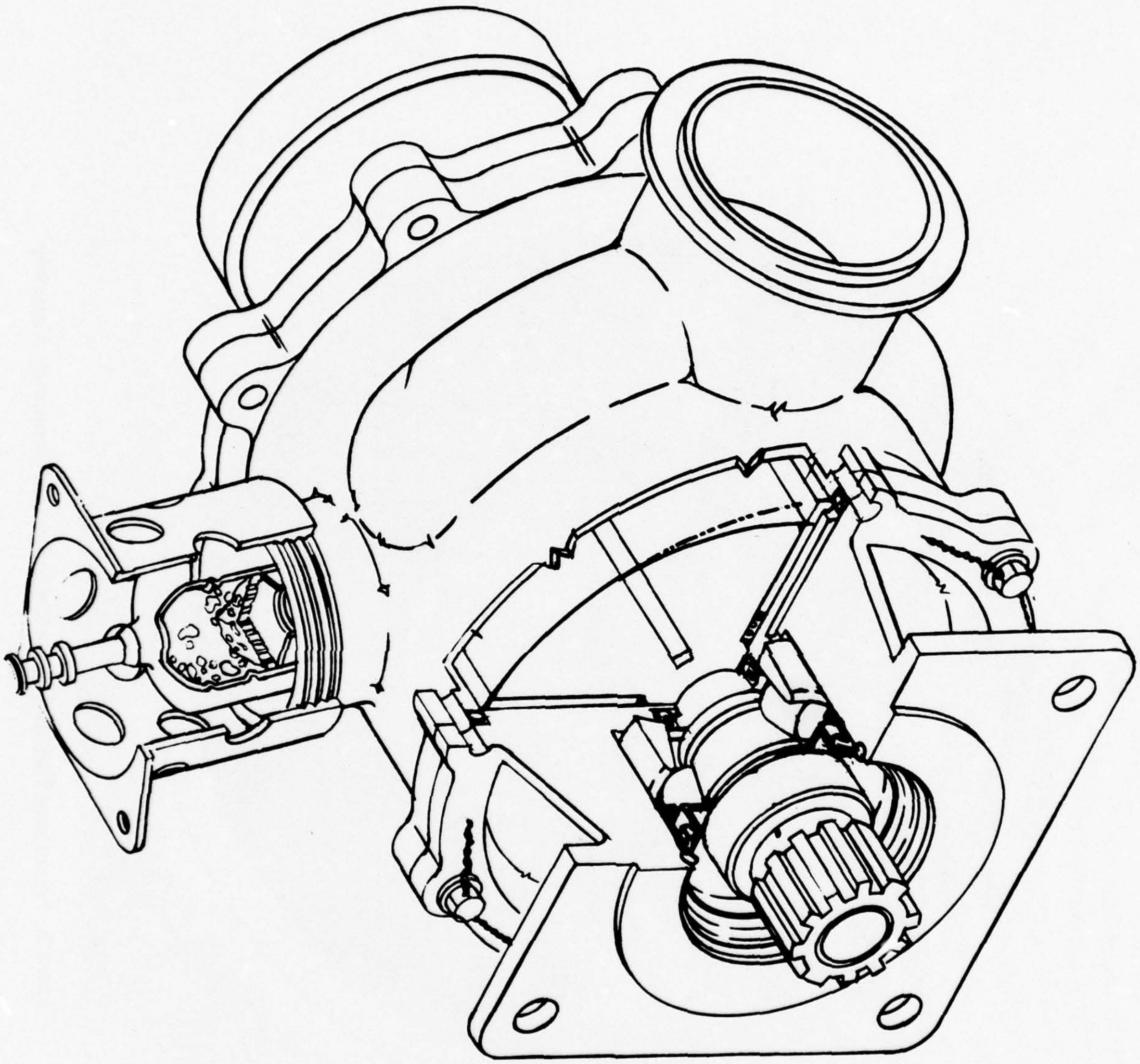


Figure 10. Isometric View of Hot Gas Rotary Valve Motor

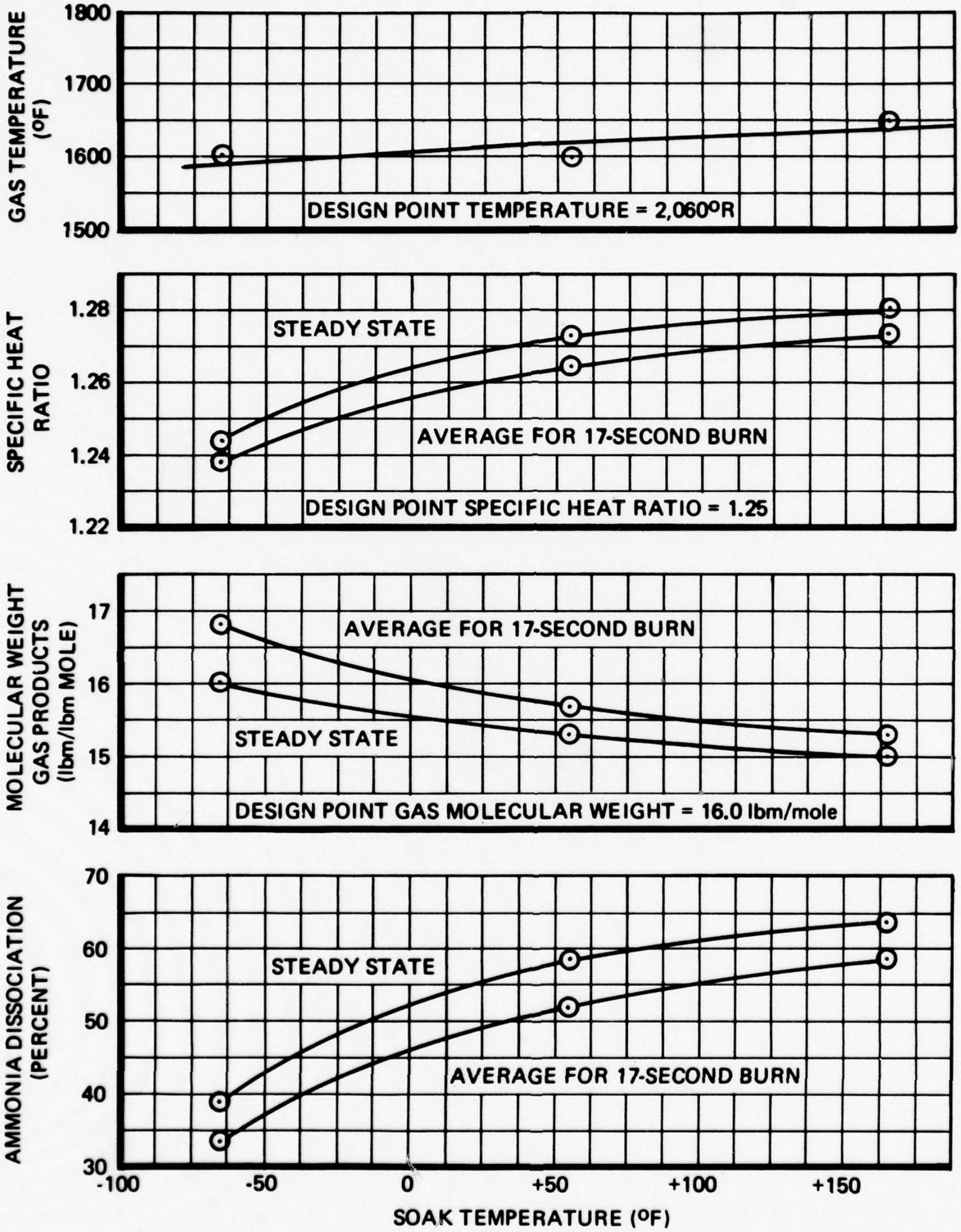


Figure 11. Performance Characteristics of Gas Generator with TSF-1 Propellant Blend
$\dot{w}$ = 0.062 lbm/sec P_c = 1000 psia

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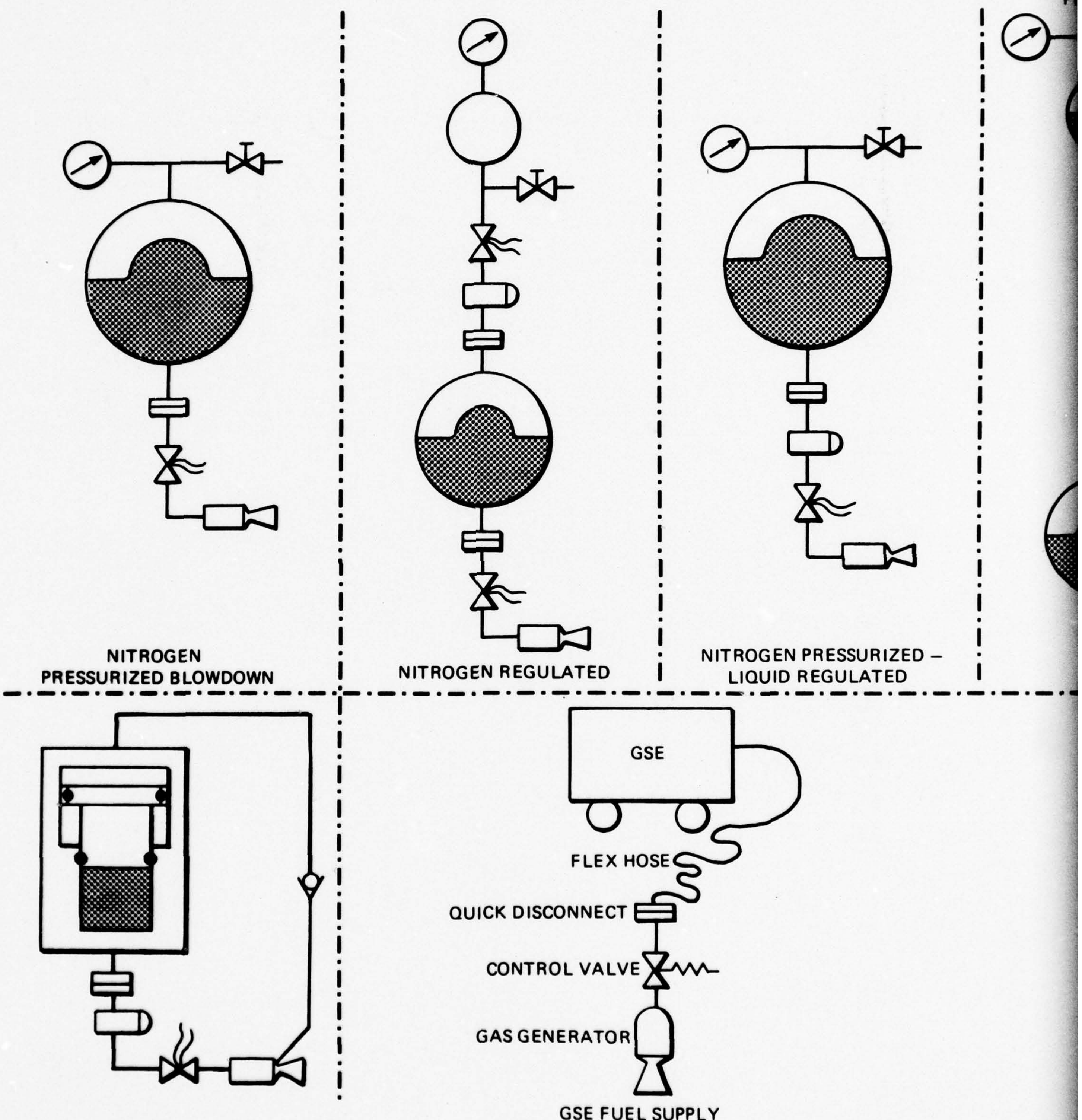

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Figure 12. Candidate Feed System Sch

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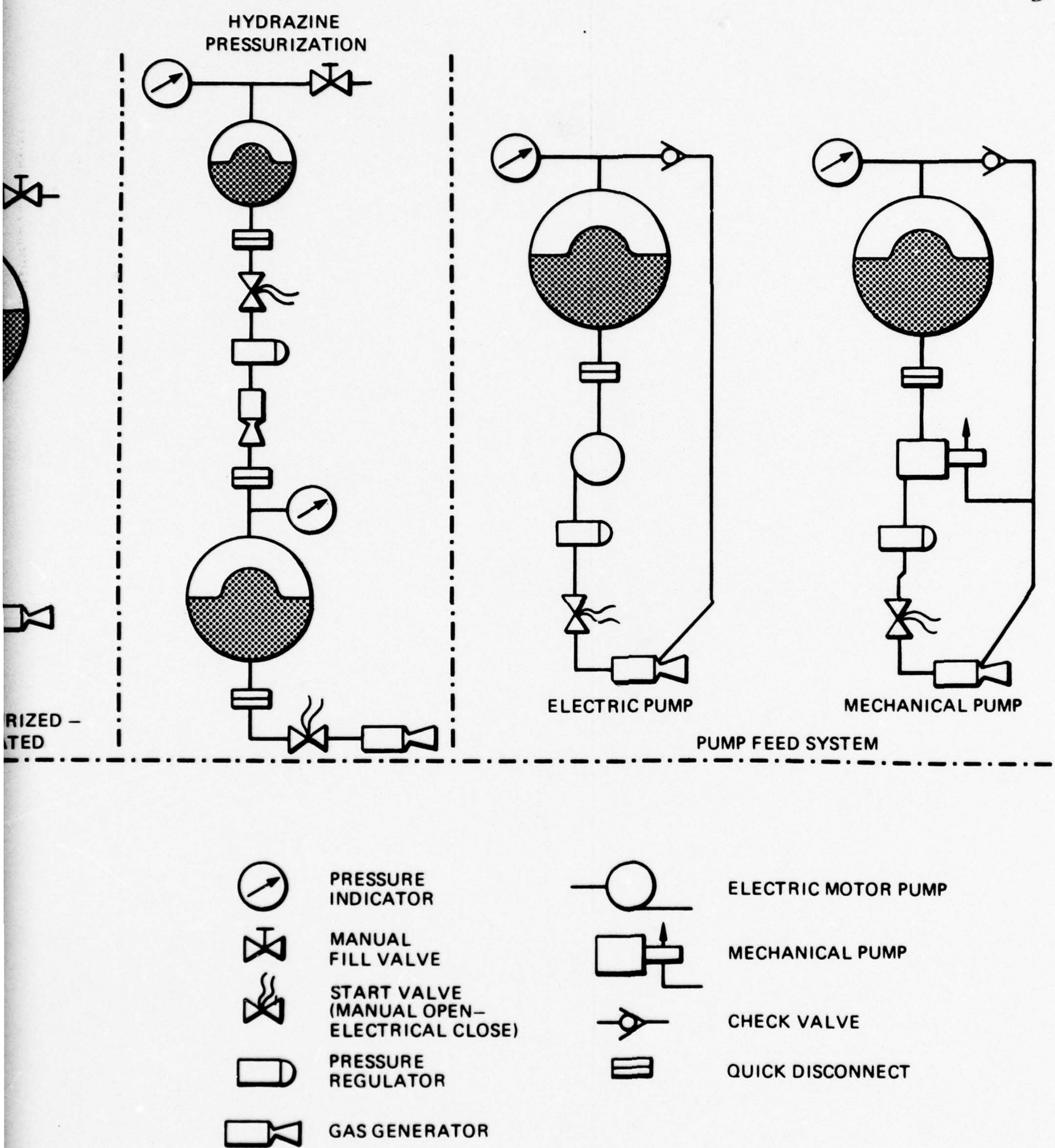


didate Feed System Schematics

a. Nitrogen pressurized blowdown
b. Nitrogen regulated
c. Nitrogen pressurized-liquid regulated
d. Hydrazine pressurized
e. Pump fed
f. Bootstrap pressurization
g. Remote (GSE) feed system

Rocket Research Company has examined each of the monopropellant hydrazine gas generating system approaches depicted in Figure 12 for the APU starter application. These candidate subsystems are described below and a trade study presented to select the preferred concept. Rocket Research Company has prior design and test experience with each of the system concepts discussed and therefore has data available to make realistic system trade studies on all of the concepts. The analysis of candidate systems has been made assuming the following specification requirements are inviolate:

a. The system shall be capable of a minimum of 20 starts prior to replacement/refilling of the propellant and pressurization tanks.
b. No maintenance of any kind is to be conducted on the system between each of the 20 starts in item a. above.
c. No power is available to initiate system operation.
d. No auxiliary equipment from the aircraft may be utilized to aid in system operation.
e. The system is to be self-contained within the aircraft.

The above constraints will immediately eliminate a portion of the systems examined. However, all potential system concepts are presented for completeness of the study.

Description and Operation of Candidate Systems

Each of the feed systems shown in Figure 12 is described in the following sections, and its applicability for use in the APU starter application is evaluated.

BLOWDOWN SYSTEM – The nitrogen-pressurized blowdown system is the simplest of all system approaches shown. Because of its simplicity, it has found wide use in space programs. The system major components consist of a fuel tank, fuel control valve, a gas generator and associated fill valve, and pressure gauge for monitoring system pressure. The fuel tank contains a quick disconnect for removal from the system, refueling, and subsequent installation back into the system.

In this system the fuel and nitrogen are contained in a common tank. The system therefore operates in a blowdown mode with the tank pressure decaying as propellant is expelled from the tank.

While this system does provide the least complex system design approach, it does have drawbacks for the APU starter application. These include:

a. Blowdown systems are larger in total volume than a nitrogen regulated system.

b. Blowdown systems are heavier in weight than nitrogen regulated systems.

c. The system provides a decaying pressure characteristic and therefore variable input to the gas generator. For this application, this characteristic has serious drawbacks. The motor must meet minimum and maximum torque output levels which limit the blowdown range for the system. In order to satisfy both of these constraints, a small blowdown ratio must be used resulting in larger tank volume and high weight.

LIQUID REGULATED SYSTEM – The liquid regulated system is similar to that described under "Blowdown System" except that a liquid regulator has been added to the system in order to produce constant pressure to the gas generator. The system therefore consists of a fuel tank, pressure regulator, fuel control valve, gas generator, and associated fill valve and pressure gauge for monitoring system status.

As in the previous system, this system contains fuel and pressurant in a common tank. As fuel is consumed, the fuel tank pressure decays, but the liquid pressure regulator maintains a constant pressure to the gas generator. While this system offers only slightly increased complexity compared to the blowdown system, it suffers similar disadvantages in that it requires additional volume and weight when compared to the nitrogen regulated system.

NITROGEN-REGULATED SYSTEM – The nitrogen-regulated system consists of a high pressure GN_2 tank, a gaseous pressure regulator, fuel tank, GN_2 and fuel control valves, a gas generator and associated fill valves, and pressure gauges to monitor system status. The system is compliant with the baseline shown in the RFP except for the addition of the control valve in the GN_2 circuit. This valve has been added to provide assurance that possible leakage past the pressure regulator in its lockup position will not overpressurize the fuel tank.

In operation, high pressure from the GN_2 tank is pressure regulated to the desired fuel tank pressure by the pressure regulator. To initiate system operation, both the GN_2 and fuel control valves are actuated which provides pressurant to the fuel tank and propellant to the gas generator. System operation is terminated by closing of the control valves. Of the systems employing inert gas pressurization, the nitrogen regulated system offers the lowest volume and weight.

HYDRAZINE PRESSURIZATION – The hydrazine pressurization system utilizes a separate hydrazine supply to pressurize the main propellant tank. Since the pressurant is stored as a liquid rather than a gas and the molecular weight of the gas products is less than that of nitrogen, this system offers reduced weight and volume over that of the previously described systems. The hydrazine pressurization system consists of a small hydrazine tank containing its own pressurant, a pressurant control valve, a liquid regulator, a pressurant gas generator, a main fuel tank, a gas generator and main fuel control valve for driving the hot gas motor, and associated fill valves and pressure gauges for monitoring system status.

To initiate system operation, the pressurant and fuel control valves are opened. Hydrazine from the pressurant tank is regulated to the desired pressure and decomposed in the pressurization gas generator. These gases pressurize the fuel tank allowing fuel to flow into the main gas generator where it is decomposed and drives the hot gas motor.

While this system minimizes system weight and volume as compared to the nitrogen regulated system, it has certain disadvantages for the APU starter which include:

a. Two separate fuel tanks which must be handled.

b. More complex system having higher cost.

c. Condensible constituents in pressurant (water and ammonia) which must be removed during fuel tank refilling resulting in higher maintenance costs.

PUMP-FED SYSTEMS – Two types of pump-fed systems are shown in Figure 12, differing only in the type of pump utilized. The systems both consist of a propellant tank, fuel pump, pressure regulator, fuel control valve, gas generator, check valve, and associated fill valve and pressure gauge for monitoring system status.

In the electric pump system, the system operation is initiated by energizing the motor pump and the fuel control valve. Pressure from the gas generator is utilized to pressurize the fuel tank as well as drive the hot gas motor. The electric pump supplies the pressure loss in the liquid circuit.

The mechanical pump system utilizes the gas generator hot gases to drive a piston which provides the required pressure amplification to compensate for the liquid pressure drop.

The electric pump option violates a "no power" system design constraint and is therefore eliminated from consideration.

In this application, both system design approaches have a disadvantage which make them unattractive for the APU starter application. In the starter application, the gas generator chamber pressure varies with motor speed. Therefore, a constant chamber pressure is not maintained, and a resultant regulated system pressure cannot be realized. As motor speed and flow rate increase, chamber pressure and thus tank pressure drop giving undesirable feed pressure characteristics and eliminating this system from consideration for the APU starter application.

BOOTSTRAP SYSTEM – The bootstrap system as shown in Figure 12 consists of a propellant tank with a differential area piston, a pressure regulator, a fuel control valve, a gas generator, and a check valve. Initially, the system is charged to a low pressure. Once the fuel control valve is actuated, propellant flows to the gas generator and is decomposed. This gas pressure is fed back to the top of the differential area piston where amplification of the pressure occurs which compensates for the liquid pressure drop and pressure is regulated to the engine.

For the APU starter, this system suffers the same problem as the pump fed systems in that the gas generator pressure output is controlled by the motor speed and is not constant. Additionally, the

differential piston tank is very heavy if the fuel load exceeds a few pounds. For these reasons and the high maintenance associated with a piston type tank, this system is eliminated from further consideration.

REMOTE FEED SYSTEM – In this system concept, the fuel supply and pressurization is remote from the gas generator and fuel control valve being in ground support equipment. This system approach is only applicable for ground starting where remote equipment could be connected for APU starting. It violates a system design constraint and is therefore removed from further consideration.

Selection of Baseline System Design Approach

Eight system design approaches for the APU starter were presented under "Description and Operation of Candidate Systems". Four of these system design approaches are eliminated in initial screening because they violate design constraints for the system. The remaining four system approaches, blowdown, liquid regulated, nitrogen regulated and hydrazine pressurized have been quantitatively evaluated against criteria and weighting factors applicable to the APU starter program. The results of this analysis are shown in Table 5. The nitrogen-regulated system ranks highest of the candidate systems and has been selected as the baseline design approach for the hydrazine fueled APU starter program.

Table 5. Evaluation of System Design Approaches

Criteria	Potential Score	Blowdown System	Liquid Regulated System	Nitrogen Regulated System	Hydrazine Pressurized System
System weight	30	10	9	25	30
System volume	30	10	10	25	30
Reliability	30	30	25	23	17
Maintainability	25	25	22	20	10
Cost	25	25	22	20	15
Performance variation with environmental temperature	20	12	20	10	17
Prior system use	20	20	10	17	5
Total	180	132	118	140	124

BASELINE SYSTEM DESCRIPTION – The baseline flight system schematic is shown in Figure 13, and a description of each of the system components is presented below.

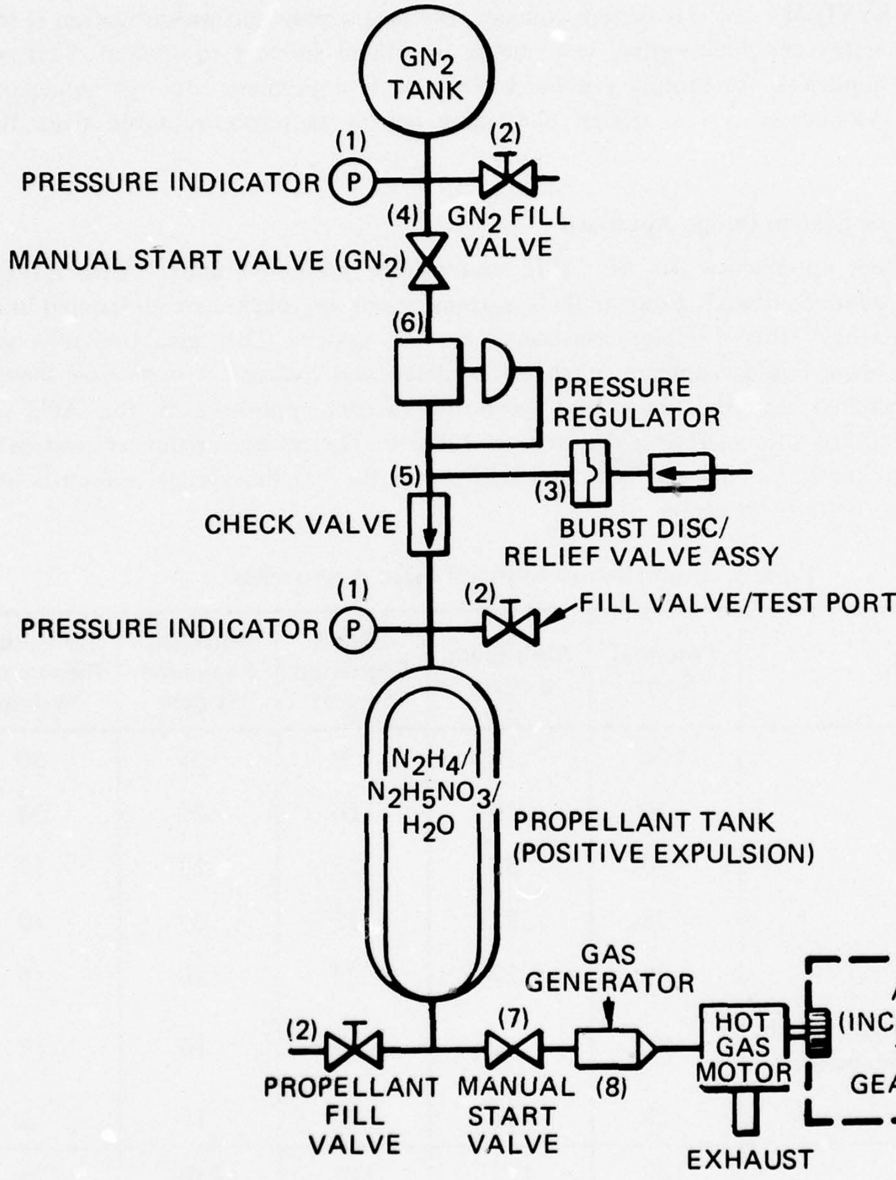


Figure 13. System Schematic – Hydrazine Fueled APU Starter

Item	Description
(1)	Pressure indicator – Provide indication of system readiness. GN_2 storage pressure together with an appropriate pressure/temperature placard provides information regarding fuel remaining.
(2)	Fill/drain valves – Provide system access for pressurant and propellant tank venting after 20 starts have been accrued.
(3)	Burst disc/relief valve assembly – This assembly provides positive sealing against leakage in normal operation but prevents propellant tank overpressure in the event of regulator failure during operation.
(4)	Manual start valve (GN_2) – The manual start valve in the GN_2 system serves the primary function of long-term pressurant sealing between system firings. This avoids dependence on the regulator as the only means of sealing. An additional function of this valve is to limit maximum system pressure at minimum ullage condition, by isolating pressurant prior to the first firing, to permit optimization of the fuel tank for minimum weight. The valve is functionally linked with the manual fuel start valve and initiates the fuel flow start sequence at the same time as it initiates pressurization function.
(5)	Check valve – This check valve serves the function of retaining pressure in the tank which will permit one start in the event an upstream failure results in loss of supply pressure.
(6)	Regulator – This component reduces the high pressure stored nitrogen to the required operating pressure in the fuel tank.
(7)	Manual start valve (fuel) – This valve is actuated "on" by the supply of regulated GN_2 from the GN_2 start valve and sequences all required functions for the start. When the turbine has reached cutoff speed, a signal (electrical, mechanical, or hydraulic) shuts the valve off and sequences all components back to the required position for the next start. This valve also provides the required flow rate control on start to achieve -65°F ignition.
(8)	Gas generator – The gas generator decomposes the fuel to produce gas at high temperature and pressure in sufficient quantity to produce the required work to start the turbine.
(9)	Hot gas motor – This component expands the high pressure hot gas and provides a torque input to the APU via a 10:1 ratio gearbox to spin up the APU turbine to starting speed.

Referring to the baseline schematic of Figure 13, the system operation is described as follows. Manual operation of the GN_2 start valve initiates a sequence which opens both the GN_2 supply valve and the fuel start valves. The opening rate of the fuel valve is controlled providing an initial low flow rate followed by a ramp rise in flow rate to prevent instantaneous buildup of excessive stall torque and excessive fuel flow to the gas generator preventing ignition at low temperature. Opening of the GN_2 control valve supplies high pressure gas to the pressure regulator where it is regulated to the desired pressure. Fuel is pressure fed to the gas generator where it is decomposed

and drives the hot gas motor. The motor output drives the turbine through a 10:1 gearbox, accelerating it to 50,000 rpm. When rated speed is reached, a speed-derived signal initiates shutdown. The shutdown signal closes both the main fuel supply valve and the GN_2 supply valve and returns the system to the ready condition for the next start.

SECTION II
STRUCTURAL AND MECHANICAL DESIGN

This section describes the basic design features of the 8 vane rotary hot gas motor.

A detailed design of the rotary motor has been completed. A full set of detailed drawings of the unit are included as Section V of this report. The top assembly drawing of the rotary motor (RRC drawing 26650) is shown in Figure 14 of this section.

The basic operating requirements for the rotary motor, hereafter referred to as the starter motor, are as follows:

1) The starter motor must be as small and lightweight as possible consistent with aircraft mounted components.
2) The starter motor must operate after extended exposures to ambient temperatures in the range of -65 to +130°F.
3) The starter motor must be capable of operating through a minimum of 1,000 full power, full duration starter operating cycles without maintenance.
4) The starter motor must be capable of operating in a successful manner when powered by the products of decomposition* of the hydrazine based propellant blend that are supplied by the hydrazine fueled hot gas supply system.
5) The starter motor must be capable of operating successfully during APU restart attempts in the event that the first start attempt is unsuccessful.
6) The starter motor shall develop torque versus speed characteristics (at the output shaft of the gearbox) with reasonable margin, consistent with the APU load characteristics shown in Figure 2.

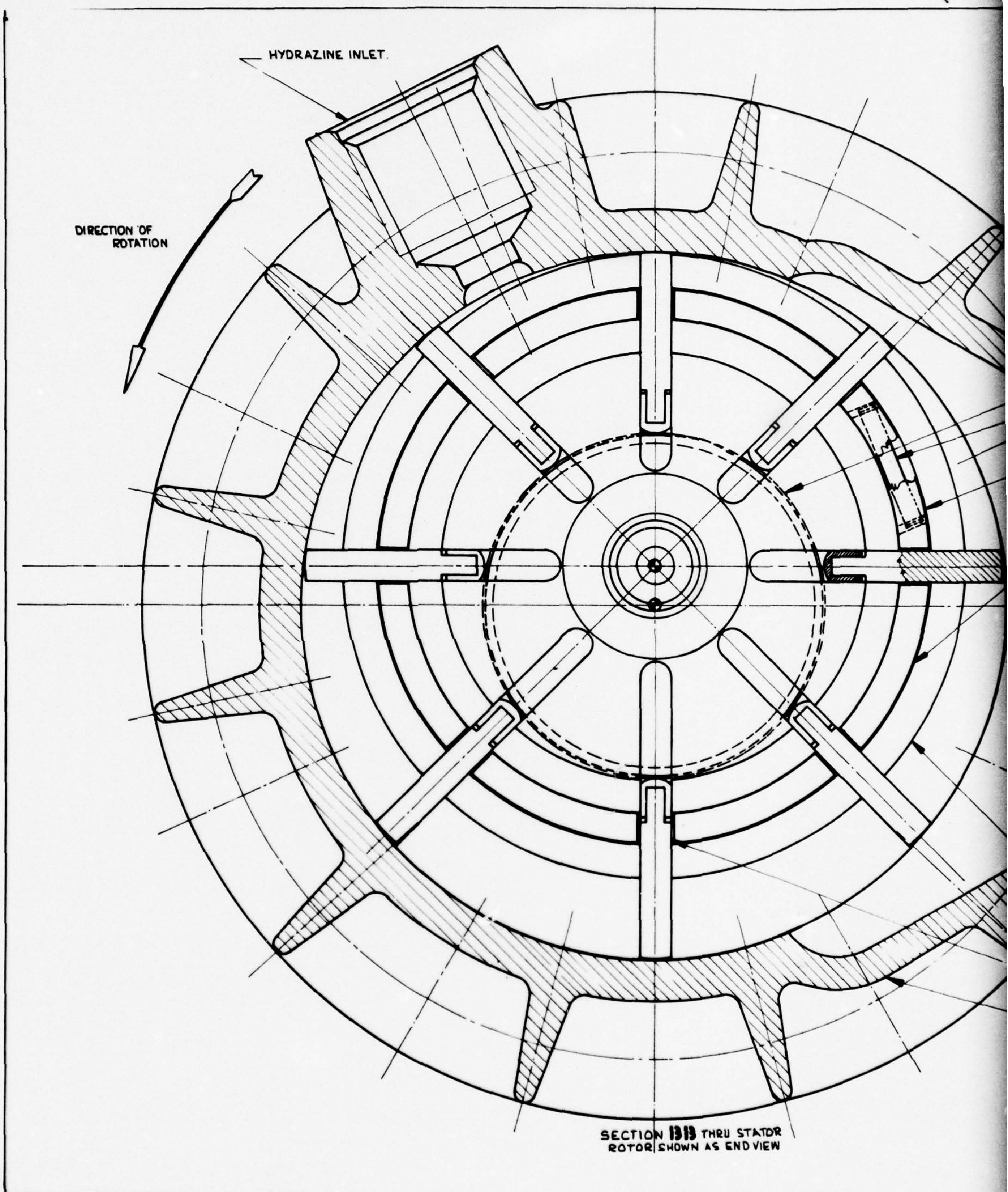
The following subsections discuss the structural and mechanical design features of the starter motor.

DESIGN DISCUSSION

The major components of the starter motor (see Figure 14) include the ball bearing mounted rotor, the rotor vanes (8 each), the stator shell, the end plates that support the rotor bearings and position the rotor eccentrically in the stator bore, and the various seals and springs. The output end of the starter motor is configured to interface with a gearbox. The gearbox would provide a 10:1 setup in shaft speed at the APU starter input pad.

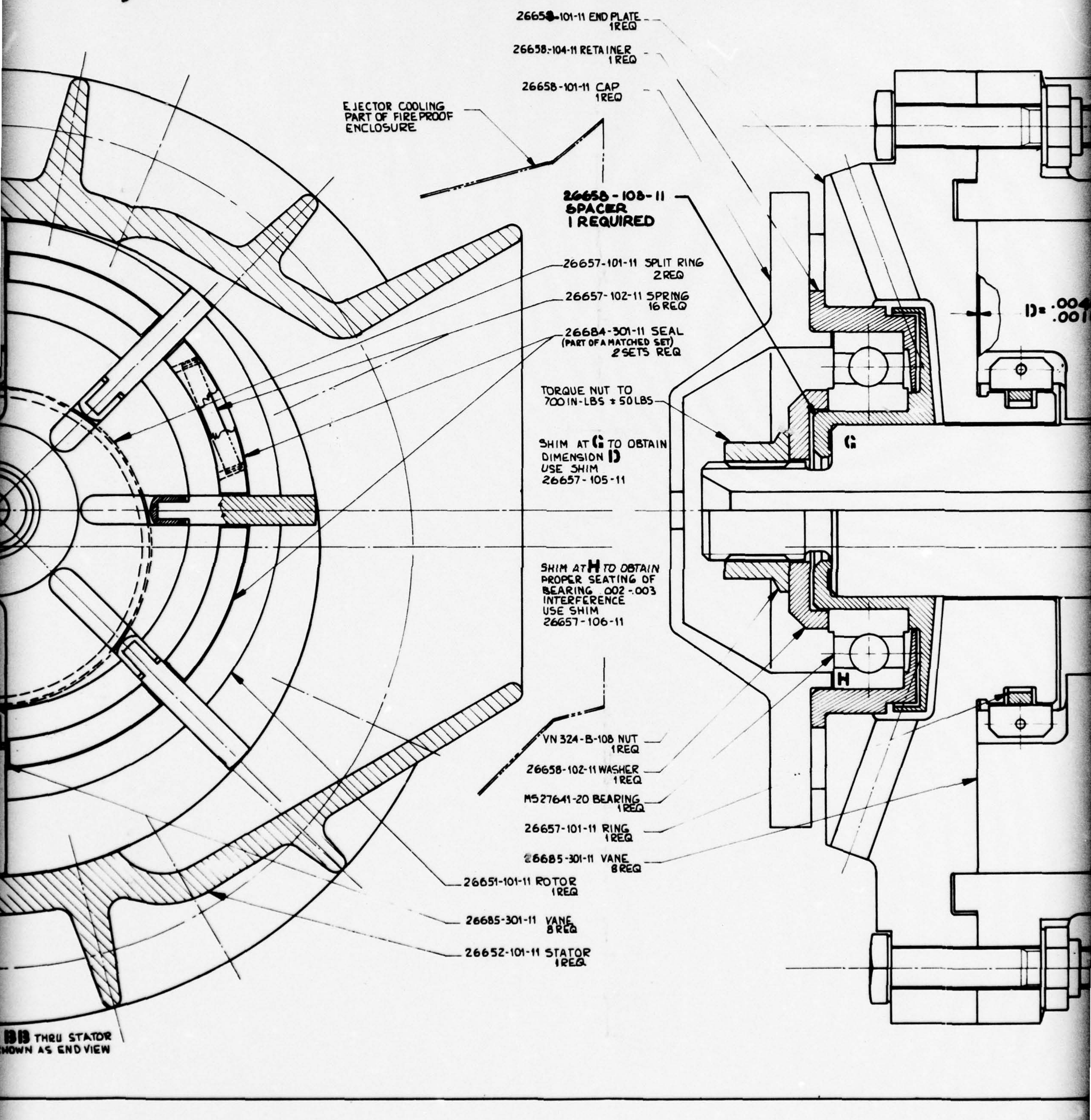
The major design efforts associated wih the development of the configuration shown in Figure 14 were related to the requirements imposed by powering the device with the high pressure hot gas as supplied by the hydrazine fueled gas generating portion of the APU starter system. Hot gas will be

*The exhaust products include nitrogen, hydrogen, ammonia, and water vapor as discussed in Section I.

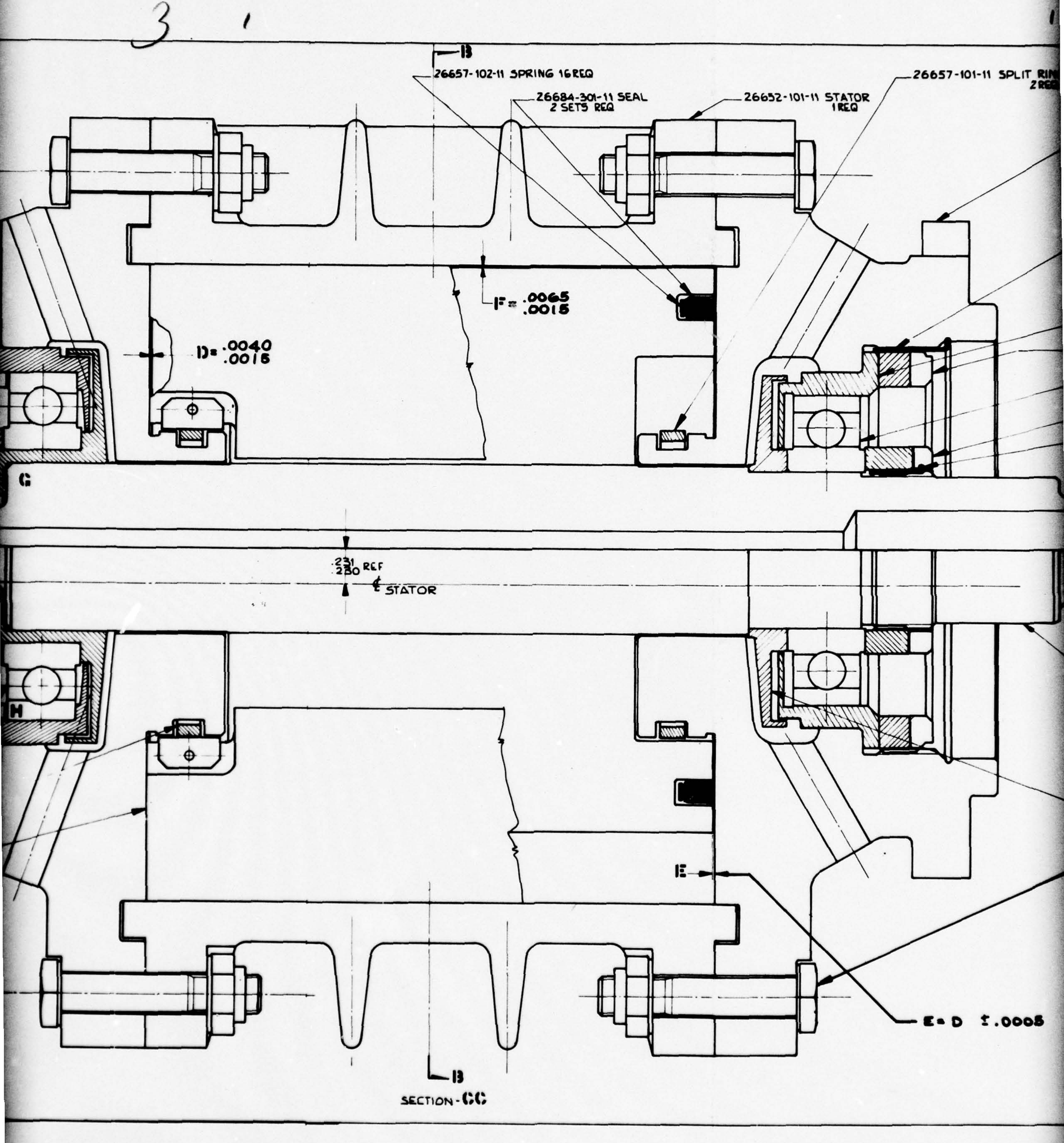

HYDRAZINE INLET.
DIRECTION OF
ROTATION
SECTION BB THRU STATOR
ROTOR SHOWN AS END VIEW

2

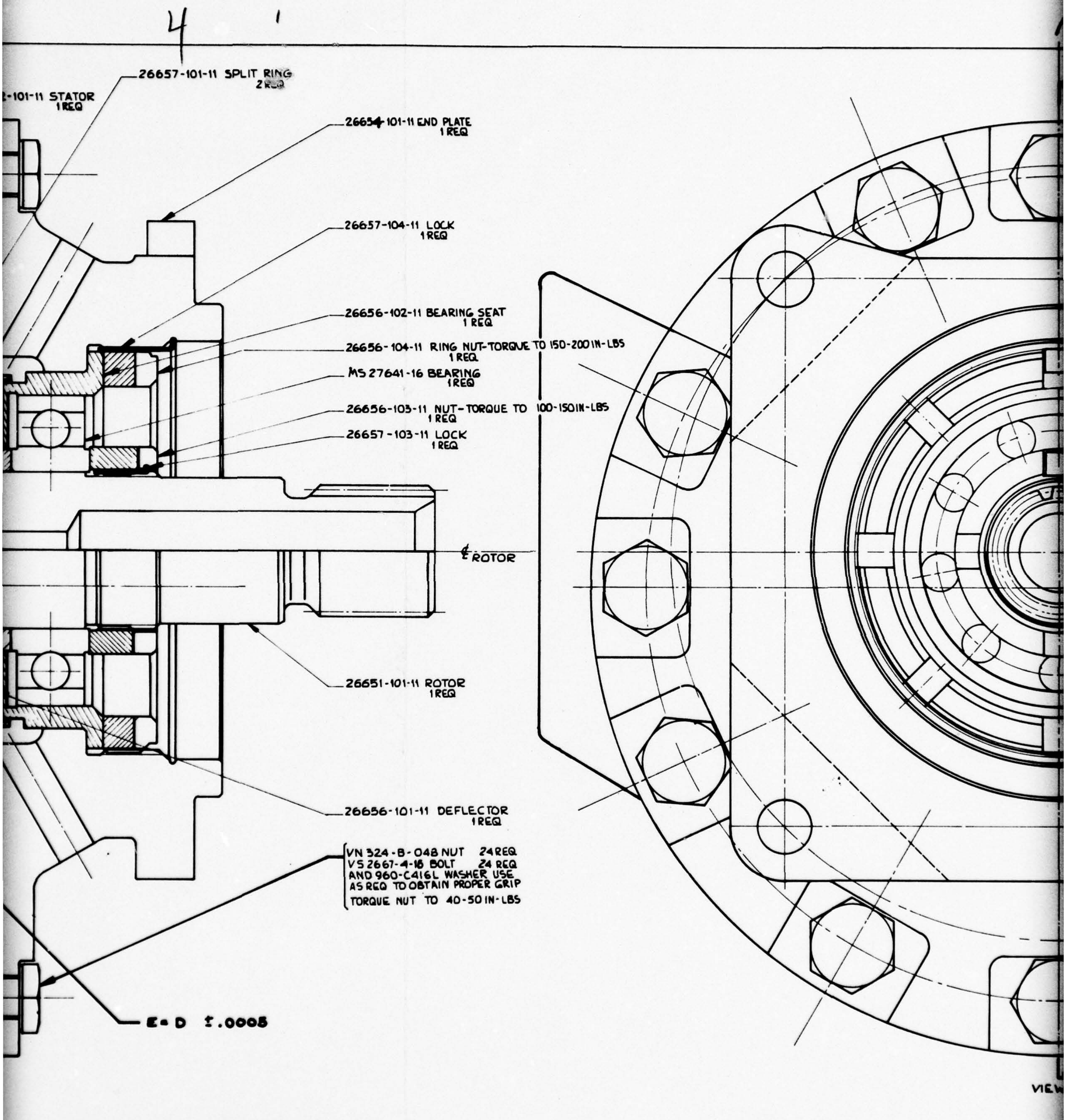
1



26658-101-11 END PLATE 1 REQ
26658-104-11 RETAINER 1 REQ
26658-101-11 CAP 1 REQ
EJECTOR COOLING PART OF FIREPROOF ENCLOSURE
26658-108-11 SPACER 1 REQUIRED
26657-101-11 SPLIT RING 2 REQ
26657-102-11 SPRING 16 REQ
26684-301-11 SEAL (PART OF A MATCHED SET) 2 SETS REQ
D= .004 .001
TORQUE NUT TO 700 IN-LBS ± 50 LBS
SHIM AT G TO OBTAIN DIMENSION D USE SHIM 26657-105-11
G
SHIM AT H TO OBTAIN PROPER SEATING OF BEARING .002-.003 INTERFERENCE USE SHIM 26657-106-11
H
VN 324-B-108 NUT 1 REQ
26658-102-11 WASHER 1 REQ
MS27641-20 BEARING 1 REQ
26657-101-11 RING 1 REQ
26685-301-11 VANE 8 REQ
26651-101-11 ROTOR 1 REQ
26685-301-11 VANE 8 REQ
26652-101-11 STATOR 1 REQ
BB THRU STATOR
HOWN AS END VIEW



3
26657-102-11 SPRING 16 REQ
26684-301-11 SEAL 2 SETS REQ
26652-101-11 STATOR 1 REQ
26657-101-11 SPLIT RIN
F = .0065 .0015
D = .0040 .0015
G
.231 .230 REF
℄ STATOR
H
E
E = D ±.0005
B
SECTION-CC



4
26657-101-11 SPLIT RING
2 REQ
-101-11 STATOR
1 REQ
26654-101-11 END PLATE
1 REQ
26657-104-11 LOCK
1 REQ
26656-102-11 BEARING SEAT
1 REQ
26656-104-11 RING NUT-TORQUE TO 150-200 IN-LBS
1 REQ
MS 27641-16 BEARING
1 REQ
26656-103-11 NUT-TORQUE TO 100-150 IN-LBS
1 REQ
26657-103-11 LOCK
1 REQ
℄ ROTOR
26651-101-11 ROTOR
1 REQ
26656-101-11 DEFLECTOR
1 REQ
VN 324-B-048 NUT 24 REQ
VS 2667-4-18 BOLT 24 REQ
AND 960-C416L WASHER USE AS REQ TO OBTAIN PROPER GRIP
TORQUE NUT TO 40-50 IN-LBS
E=D ±.0005
VIEW

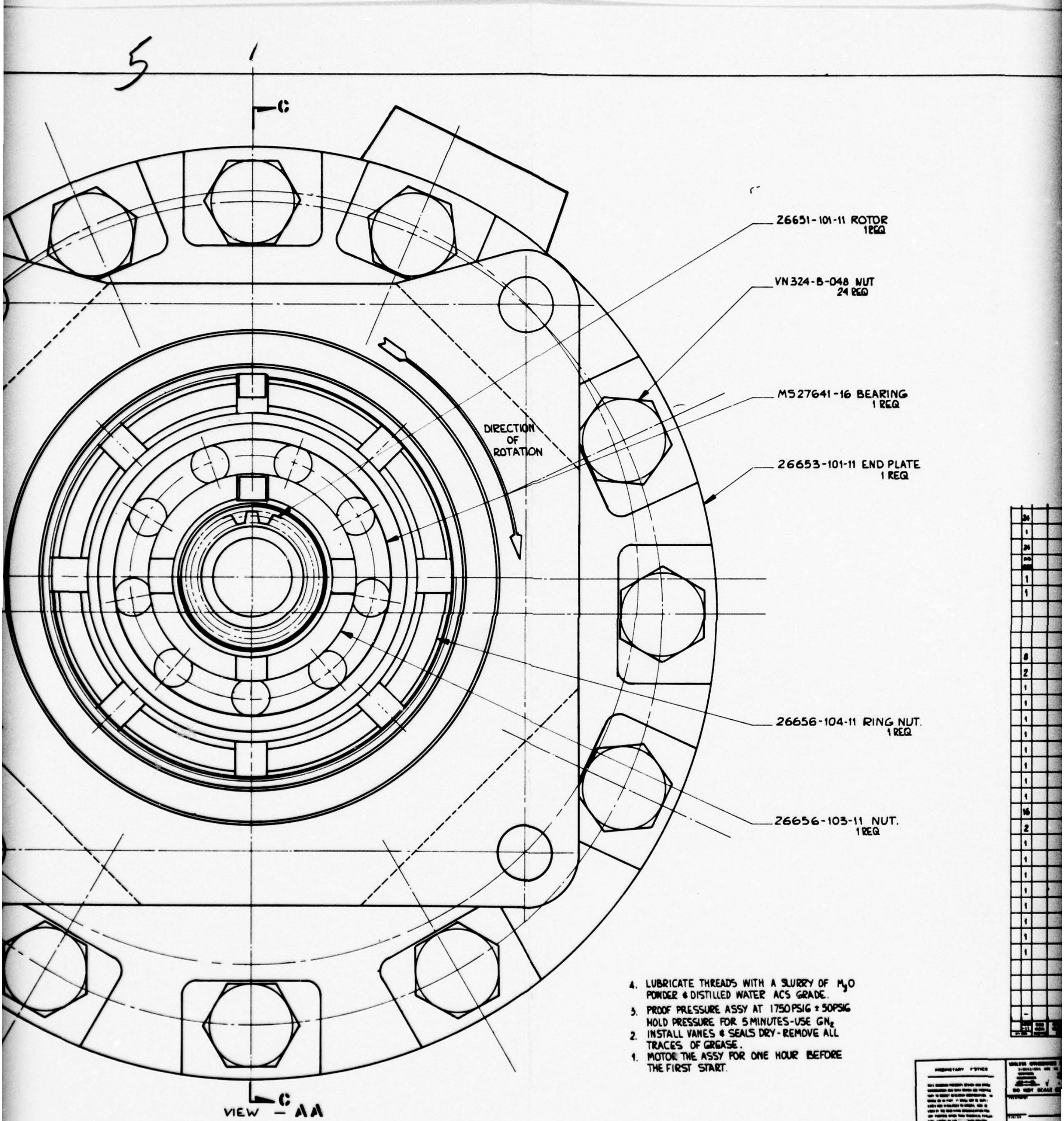
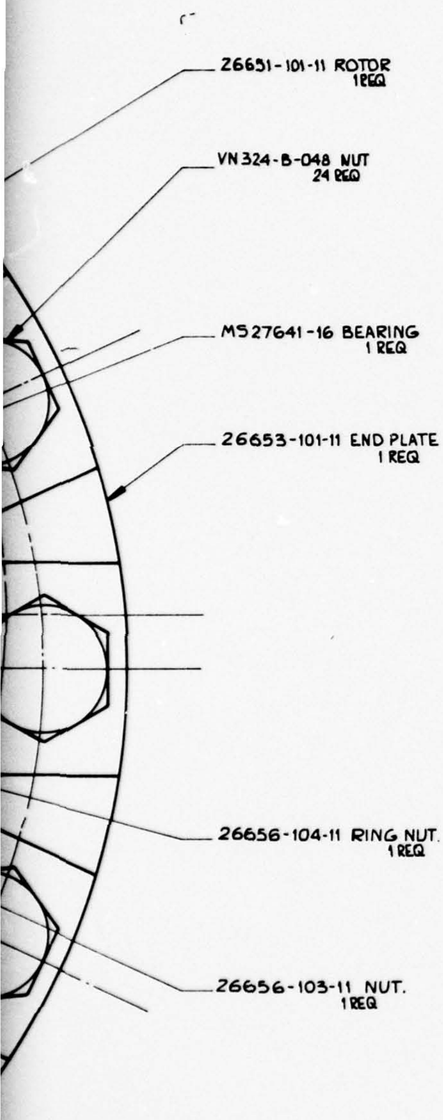


Figure 14. Starter Assembly Hydrazine



QTY		CODE IDENT NO	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION		ITEM NO
24			VN324-B-048	NUT		VOISHAN CORP.		
1			VN324-B-108	NUT		VOISHAN CORP.		
24			VS2627-4-16	BOLT		VOISHAN CORP.		
[illegible]			AND960-C4	WASHER				
1			MS27641-20	BEARING				
1			MS27641-16	BEARING				
8			26685-301-11	VANE ASSY	PURE CARBON CO. ST. MARYS PENNA.			
2			26684-301-11	SEAL SET	PURE CARBON CO. ST. MARYS PENNA.			
1			26658-104-11	RETAINER				
1			26658-103-11	SPACER				
1			26658-102-11	WASHER				
1			26658-101-11	END CAP				
1			26657-106-11	SHIM				
1			26657-105-11	SHIM				
1			26657-104-11	LOCK LARGE				
1			26657-103-11	LOCK				
16			26657-102-11	SPRING				
2			26657-101-11	SPLIT RING				
1			26656-104-11	RING NUT				
1			26656-103-11	NUT				
1			26656-102-11	BEARING SEAT				
1			26656-101-11	DEFLECTOR				
1			26654-101-11	END PLATE				
1			26653-101-11	END PLATE				
1			26652-101-11	STATOR				
1			26651-101-11	ROTOR				
-			-301-11	ASSY				

LIST OF MATERIALS

. LUBRICATE THREADS WITH A SLURRY OF M_oO POWDER & DISTILLED WATER ACS GRADE.
. PROOF PRESSURE ASSY AT 1750 PSIG ± 50 PSIG HOLD PRESSURE FOR 5 MINUTES - USE GN_2
. INSTALL VANES & SEALS DRY - REMOVE ALL TRACES OF GREASE.
. MOTOR THE ASSY FOR ONE HOUR BEFORE THE FIRST START.

PROPRIETARY NOTICE

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

DO NOT SCALE DRAWING

ROCKET RESEARCH CORPORATION
REDMOND, WASHINGTON

TITLE
STARTER ASSY.
HYDRAZINE

21562 | 26650

tarter Assembly Hydrazine

delivered to the starter motor inlet port at nominal conditions of 1,000 psig and 1,600°F. Successful system operation will require minimal hot gas leakage across the rotor vane surfaces and shaft seals. Excess gas leakage would degrade the power output characteristics of the starter motor and increase the quantity of fuel required for each start cycle. Additionally, provisions for thermal growth are provided on all moving parts to avoid component damage and performance degradation during the transient heating conditions that occur during each starter operating cycle. Due consideration is also imposed on the selection of materials for each component to assure compatibility with the hot gas supplied by the hydrazine fueled gas generating subsystem.

The design approach and the major design features of the starter motor are discussed in the following subsections. Detailed design drawing of each starter motor component are presented in Section V of this report.

STRUCTURAL CHARACTERISTICS

Gas Leakage

The following major provisions have been incorporated into the starter motor design to minimize gas leakage.

1) Vane Sealing – The vane material is carbon providing self-lubrication at all moving contact points. A surface finish of 8 micro inches (8/) is specified for the contact surfaces of each vane and all surfaces in contact with each vane.

   Vane leakage at the stator wiping surface will be minimized by the 8/ surface finish on the stator bore. A light spring force is applied to each vane by the P/N 26657-101-11 split ring which is supported by the cam surface on each end plate. The spring loading feature assures good vane to stator contact during initial starting and low-speed rotor operating periods. The contact pressure at the vane to stator line of contact increases as the rotor speed builds up due to centrifugal forces acting on the vane mass. The final shape of the carbon blade at the stator contact surface will be established by motoring the unit with high pressure gaseous nitrogen after the initial assembly operation.

   The leak path between the end plates and the rotor is minimized by dimensional tolerance control (see Dimension "D" in the side view of the starter motor, Figure 14) by installing a shim at "G" during assembly. Additionally, spring-loaded carbon face seals, P/N 26684-301-11, are installed between each vane (16 places) and the end plates to reduce the leakage in the "D" clearance gap.

   A small amount of leakage will be unavoidable between the end of each vane and the end plates and between each vane and its retention slot in the rotor. Gas leakage between the end of each vane and the end plates will be minimized by establishing a zero clearance tolerance in this dimension during the initial assembly operation. Gas leakage between each blade and its retention slot in the rotor will be minimized by allowing the vanes to cock slightly, due to rotational drag at the stator rubbing surface.

2) Rotor Bearing Gas Leakage – A very considerable design effort has been expended to reduce gas leakage into the rotor bearing areas, and minimize bearing heating from the

hot gas leak source. Minimum clearance has been allowed, considering rotor deflection and thermal growth, in the bore gap between the end plates and rotor shaft to provide a maximum flow resistance to hot gas leakage into the end cap bearing cavities. The unavoidable flow of hot gas into the bearing cavities is routed overboard preferentially through a series of four 1/4-inch diameter holes in the P/N 26553/26554-101-11 end plates. The direct impingement of hot gas leakage on the rotor shaft bearings is minimized by the labyrinth formed by the P/N 26556-101-11 deflector, the P/N 26556-102-11 bearing seat at the output end of the starter motor, the P/N 26558-103-11 spacer, and the P/N 26658-104-11 retainer at the other end of the starter motor.

Major Component Design Detail

A stress analysis of each major component has been completed, as summarized in Figures 15 through 29, which combined gas pressure loads, inertia loads, and thermal transient heating effects. Table 6 presents a summary of the maximum stress level and the strength of materials for the rotor, stator, end plates, and rotor vanes.

The maximum stress in the rotor occurs at the root of the pie section formed by adjacent vane slots. The maximum stress in the stator case and end plates occurs at the root section, formed immediately inboard of the bolt pattern. The maximum stress in the vanes occurs during start, when the cold vanes are flexed over the curved blade slots in the rotor. The unique design features of the major components of the hot gas motor components are as follows:

1) Starter Motor Assembly, General – During each start cycle, the starter motor assembly is subjected to internal pressure loads and transient heating effects by the hot gas driving media. Analysis has shown that the stator case will expand diametrically and axially at a greater rate than the rotor. The bearing that supports the rotor at the output end of the starter motor floats to accommodate axial expansion. The bearing at the other end of the motor is fixed.

2) Rotor and Vanes – Hot gas impingement on the rotor and vanes during starter motor operation, results in severe temperature gradients that effect the clearance between the vanes and the slots in the rotor that support and guide the vanes. In order to minimize the clearance between the vanes and slots (for minimum gas leakage), while avoiding mechanical interference due to thermal expansion effects, analysis has shown that the rotor slot geometry noted in Figure 30 will be required.

   The trailing edge contour in the rotor vane slot allows the vane to flex under initial cold start conditions. The amount of flexure decreases as the rotor and blade heat up, and thermal expansion effects reduce the trailing edge gap.

3) End Plates – The end plates locate the rotor support bearings, such that the centerline of the rotor is parallel to the centerline of the stator bore, but displaced by the 0.231-inch eccentricity requirement. The end plates also include the integral cam surfaces that assist the vanes in following the stator bore during the expansion portion of the rotary motor operating cycle.

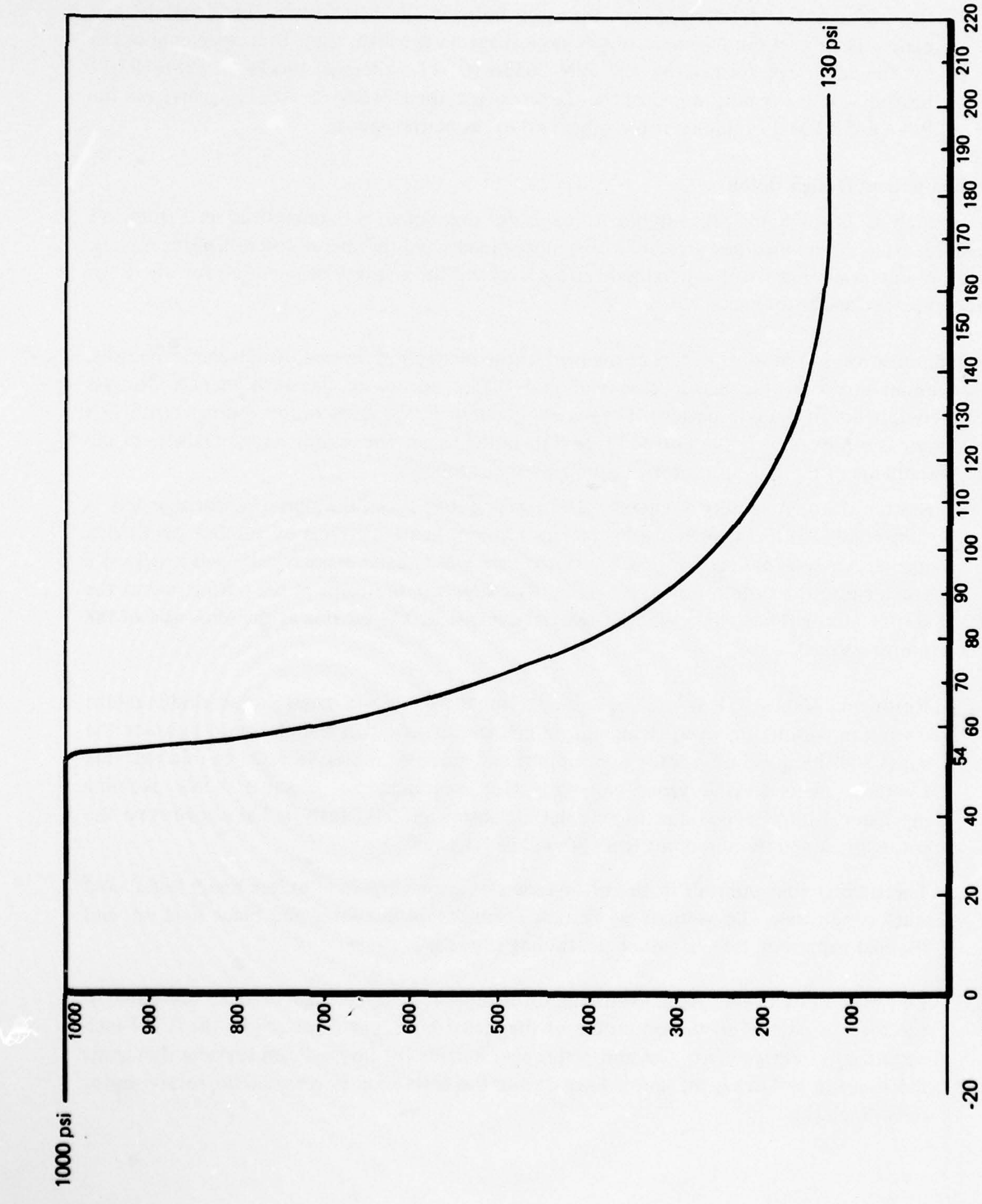
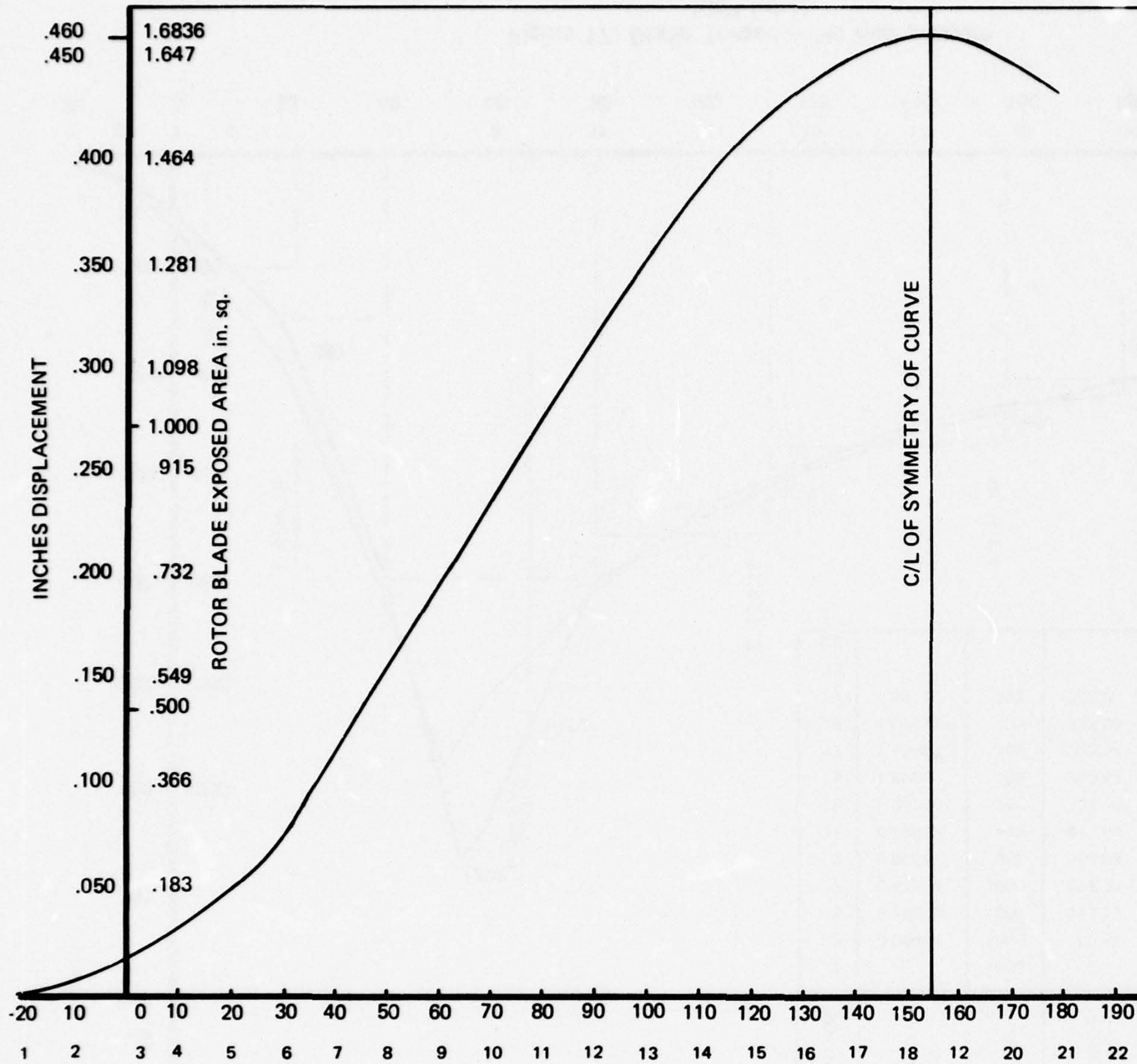
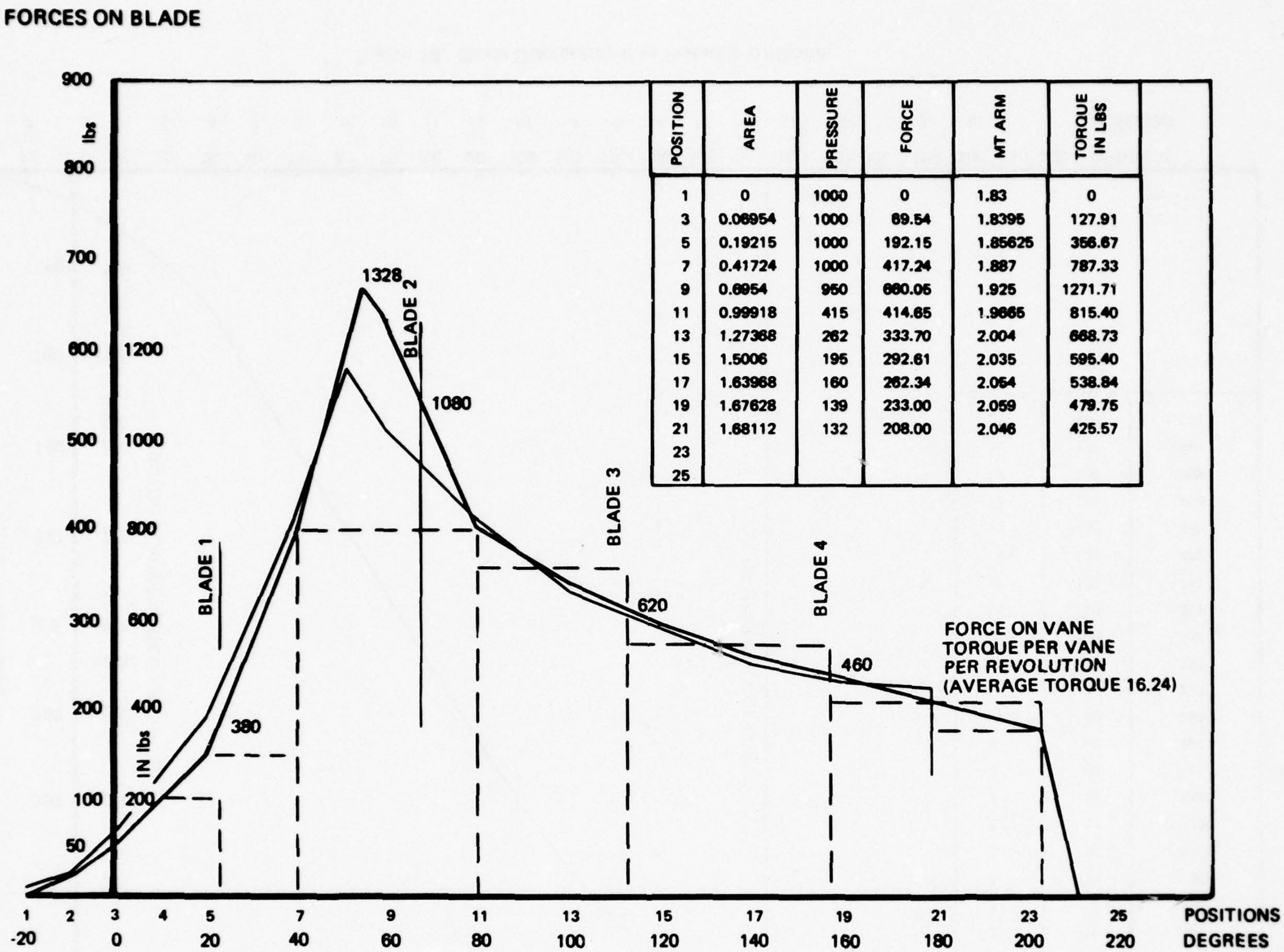


Figure 15. Pressure Distribution on Rotor
25° Inlet



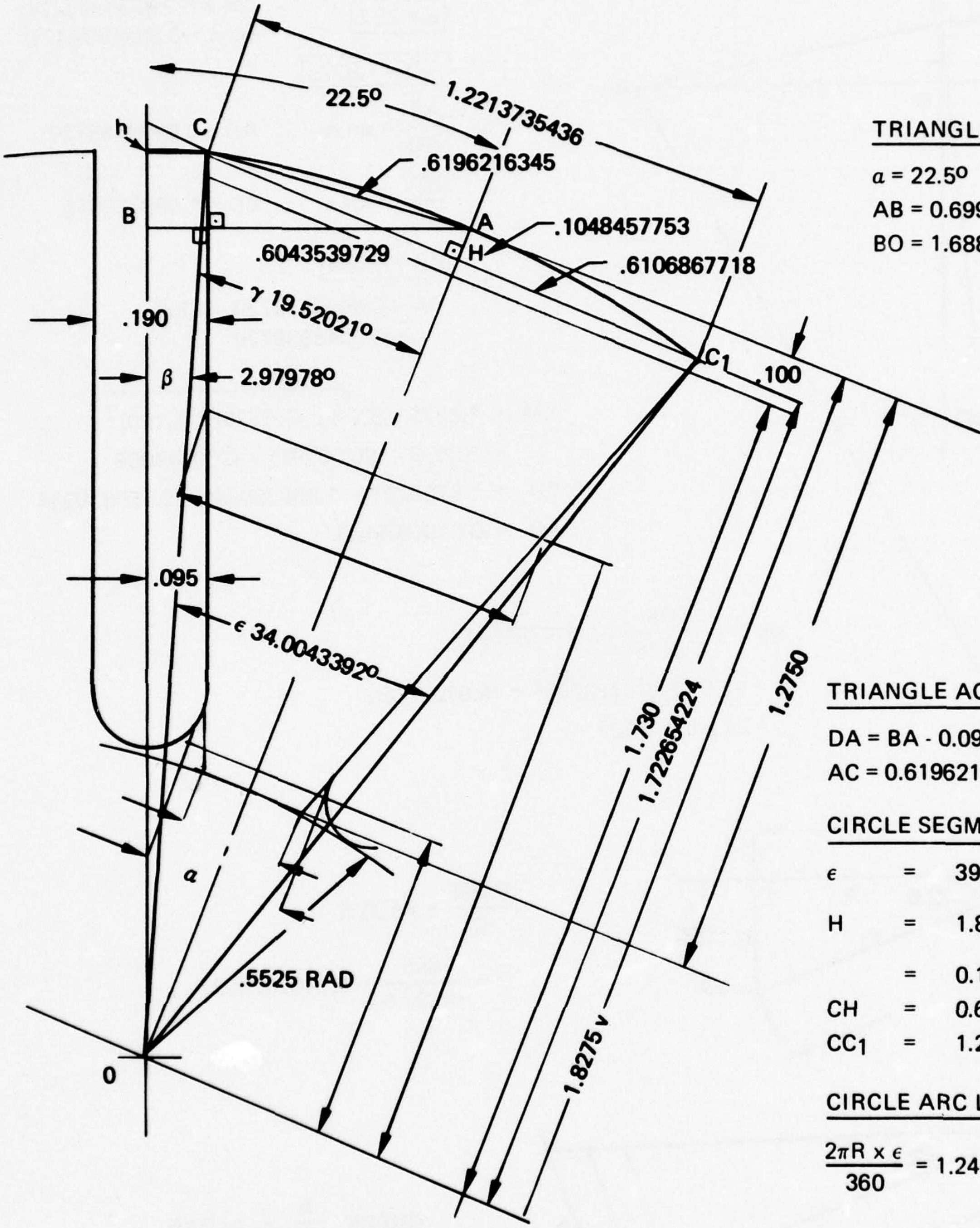
POSITION	DEGREES	DISPLACEMENT INCH
1	-20	0
2	-10	.006
3	0	.019
4	10	.032
5	20	.0525
6	30	.0730
7	40	.114
8	50	.151
9	60	.190
10	70	.230
11	80	.273
12	90	.310
13	100	.348
14	110	.388
15	120	.410
16	130	.432
17	140	.448
18	150	.458
19	160	.458
20	170	.448
21	180	.432

Figure 16. Blade Displacement vs Rotation of Rotor



POSITION	AREA	PRESSURE	FORCE	MT ARM	TORQUE IN LBS
1	0	1000	0	1.83	0
3	0.06954	1000	69.54	1.8395	127.91
5	0.19215	1000	192.15	1.85625	356.67
7	0.41724	1000	417.24	1.887	787.33
9	0.6954	950	660.06	1.925	1271.71
11	0.99918	415	414.65	1.9665	815.40
13	1.27368	262	333.70	2.004	668.73
15	1.5006	195	292.61	2.035	595.40
17	1.63968	160	262.34	2.064	538.84
19	1.67628	139	233.00	2.059	479.75
21	1.68112	132	208.00	2.046	425.57
23					
25					

Figure 17. Static Torque – No Backpressure
(25° Inlet)



TRIANGLE AOB

$\alpha = 22.5^{\circ}$ AO = 1.8275

AB = 0.6993539729

BO = 1.6883898

TRIANGLE ACD

DA = BA - 0.095 = 0.6043539729

AC = 0.6196216345 INCH

CIRCLE SEGMENT CAC_1

ϵ = 39.0043392°

H = $1.8275\ 1 - \cos\left(\frac{\epsilon}{2}\right)$

= 0.1048457759 INCH

CH = 0.6106867718 INCH

CC_1 = 1.2213735436 INCH

CIRCLE ARC LENGTH

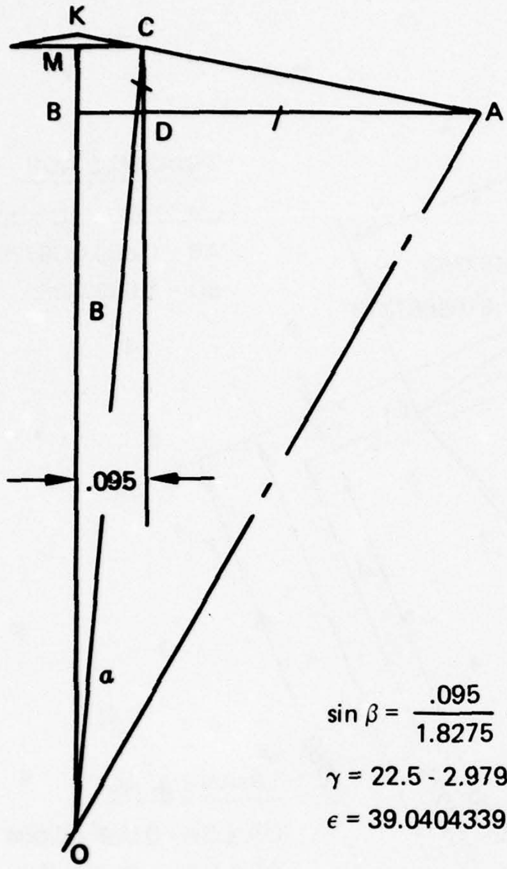
$$\frac{2\pi R \times \epsilon}{360} = 1.244078194 \text{ INCH}$$

$$h = 1.8275 - .5\sqrt{4 \times (1.8275)^2 - (.190)^2} = 0.00247089 \qquad ho = 1.82502911$$

$$\sin\beta = \frac{.095}{1.8275} \qquad \beta = 2.979783041^{\circ}$$

$$\gamma = 19.52021696^{\circ} \qquad \epsilon = 39.040433920^{\circ}$$

Figure 18. Rotor Slot Geometry (Cold)



$\boxed{a = 22.5}$ $\cos a = 0.9238795326$

$\sin a = 0.3826834325$

$\boxed{AO = 1.8275}$

$$\frac{AB}{AO} = \sin a \qquad AB = 0.6993539729$$

$$\frac{BO}{AC} = \cos a \qquad BO = 1.688389846$$

$\boxed{BD = 0.095}$

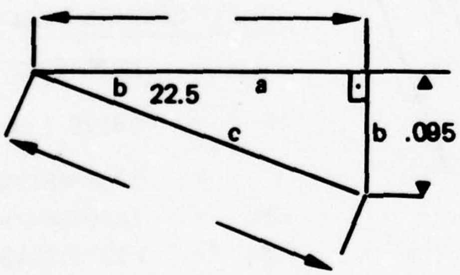
$$DA = 0.6993539729 - 0.095 = 0.6043539729$$

$$KM = 1.8275 - .5\sqrt{4 \times (1.8275)^2 - (.190)^2}$$
$$= 1.8275 - 1.82502911 = 0.00247089$$
$$CD = 1.82502911 - 1.688389846 = 0.136639264$$
$$AC = 0.6196079511$$

$$\sin \beta = \frac{.095}{1.8275} = 2.979783041^{\circ}$$

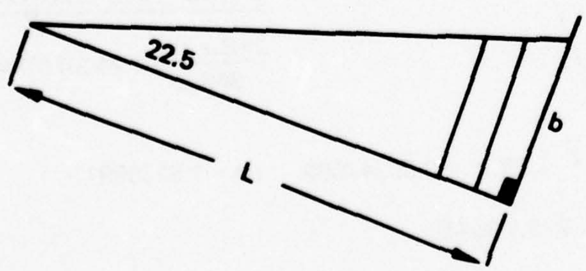
$$\gamma = 22.5 - 2.979783041^{\circ} = 19.52021696$$

$$\epsilon = 39.04043392^{\circ}$$



$$\frac{0.095}{C} = \sin 22.5$$

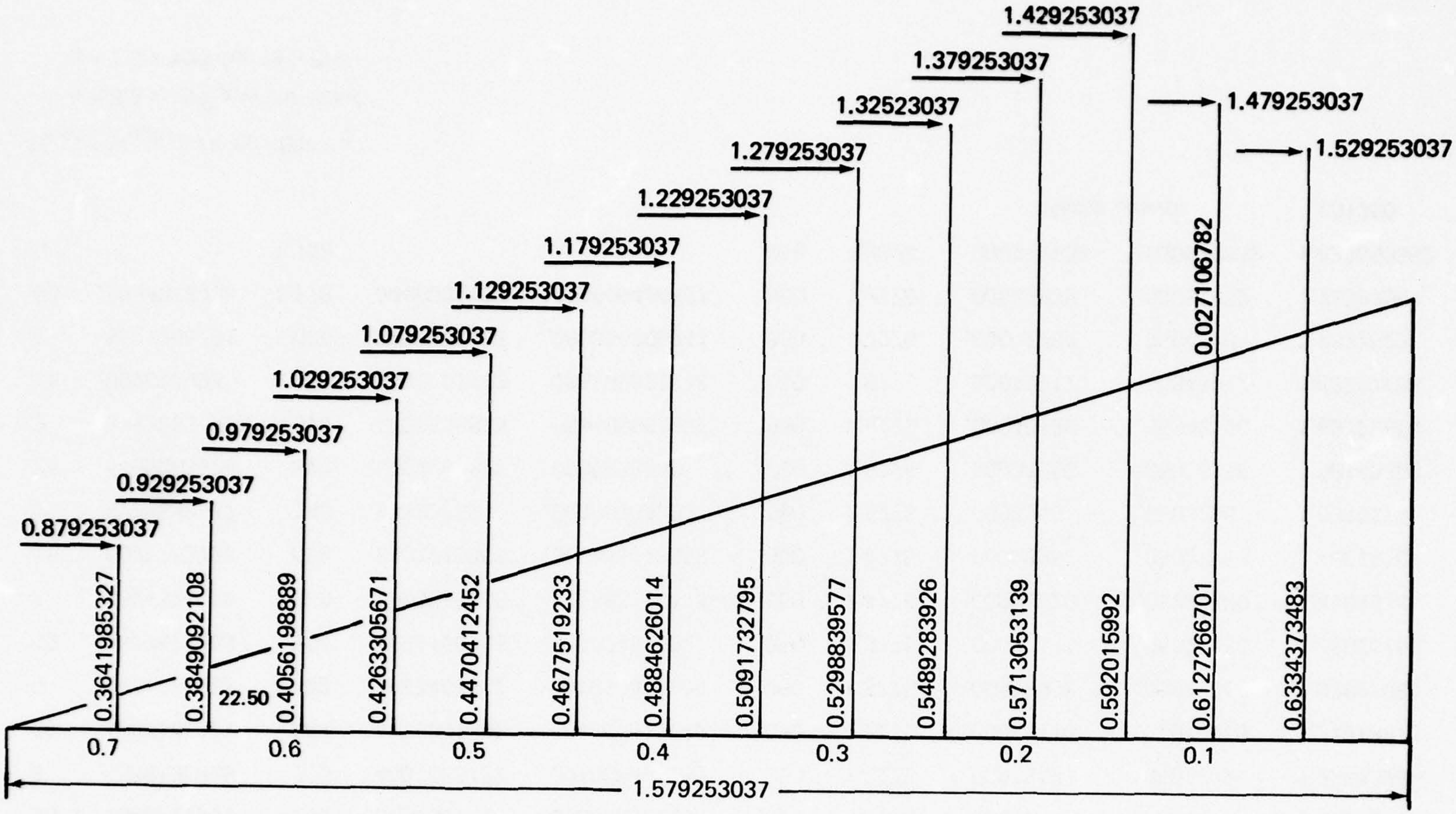
$$C = \frac{.095}{\sin 22.5} = 0.2482469632$$



CHECK $\frac{b}{L}$ **= ty 22.5**

b = L ty 22.5

Figure 19. Rotor Slot Geometry (Cold)



tg 22.5 = 0.4142135624

Figure 20. Rotor Slot Geometry (Cold)

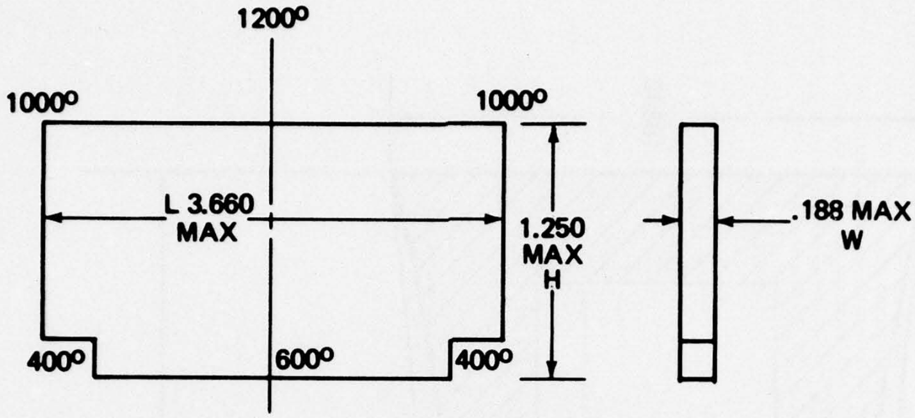
Pos	Width Cold	Temp	Width Hot	ΔW	Lengths Cold	Coord	ΔL Hot	Length Hot	Coord Length
.7	.3641985327	200	.3648395221	.00064098941	1.1275		.0019844	1.1294844	1.1294844
.65	.3849092108	250	.385756011	.00084680026	.050	1.1775	.00011	.050011	1.1794954
.6	.4056198889	305	.4067085727	.001088683782	.050	1.2275	.0001342	.0501342	1.2296296
.55	.4263305671	364	.4276961891	.001365622072	.050	1.2775	.00016016	.05016016	1.27978976
.5	.4470412452	432	.4487407172	.001699471999	.050	1.3275	.00019008	.05019008	1.32997984
.45	.4677519233	504	.4691158185	.00207457333	.050	1.3775	.00022176	.05022176	1.3802016
.4	.4884626014	580	.4909557145	.002493113117	.050	1.4275	.00025520	.05025520	1.4304568
.35	.5091732795	658	.5121215965	.002948316958	.050	1.4775	.00028952	.05028952	1.4807458
.3	.5298839577	740	.533334562	.00340604333	.050	1.5275	.0003256	.0503256	1.5310714
.25	.5489283926	824	.5529087822	.0039838956	.050	1.5775	.00036256	.05036256	1.58143396
.2	.5713053139	912	.5758903818	.004585067927	.050	1.6275	.00040128	.05040128	1.63183524
.15	.592015992	998	.5972153132	.005199321248	.050	1.6775	.00043912	.05043912	1.68227436
.1	.6127266701	1,086	.6185823763	.005855706241	.050	1.7275	.00047784	.05047784	1.7327522
.05	.6334373483	1,178	.6400038132	.006566464927	.050	1.7775	.00051832	.05051832	1.78327052
.0		1,198			.055	1.8325	.000579832	.050579832	1.833850352
							Radial growth		.001350

$W_{hot} = W_{cold} \times (\text{temp} - 68) \times \alpha$

$\alpha = 8.8 \times 10^{-6}$ aver for René

$\alpha = 7.3 \times 10^{-6}$ for 15-5 PH

Figure 21. Rotor Slot Geometry (Hot)



COEFFICIENT OF THERMAL EXPANSION $a = 2.2 \times 10^{-6}$

L_{COLD}	=	3.660	
$L_{1100°}$	=	$1100 \times 2.2 \times 10^{-6} \times 3.660 = .00885$	3.668872
H_{COLD}	=	1.250	
$H_{750°}$	=	$750 \times 2.2 \times 10^{-6} \times 1.250 = .0020625$	1.2520625
W_{COLD}	=	0.188	
$W_{900°}$	=	$900 \times 2.2 \times 10^{-6} \times .188 = .00037224$	0.18837224
$L_{1200°}$	=	$1200 \times 2.2 \times 10^{-6} \times 3.660 = .0096624$	3.6696624
$H_{1200°}$	=	$1200 \times 2.2 \times 10^{-6} \times 1.25 = .0033$	1.2533
$W_{1200°}$	=	$1200 \times 2.2 \times 10^{-6} \times .188 = .00049632$	0.188496
$W_{600°}$	=	$600 \times 2.2 \times 10^{-6} \times .188 = .00024816$	0.18824816

Figure 22. Vane Thermal Expansion

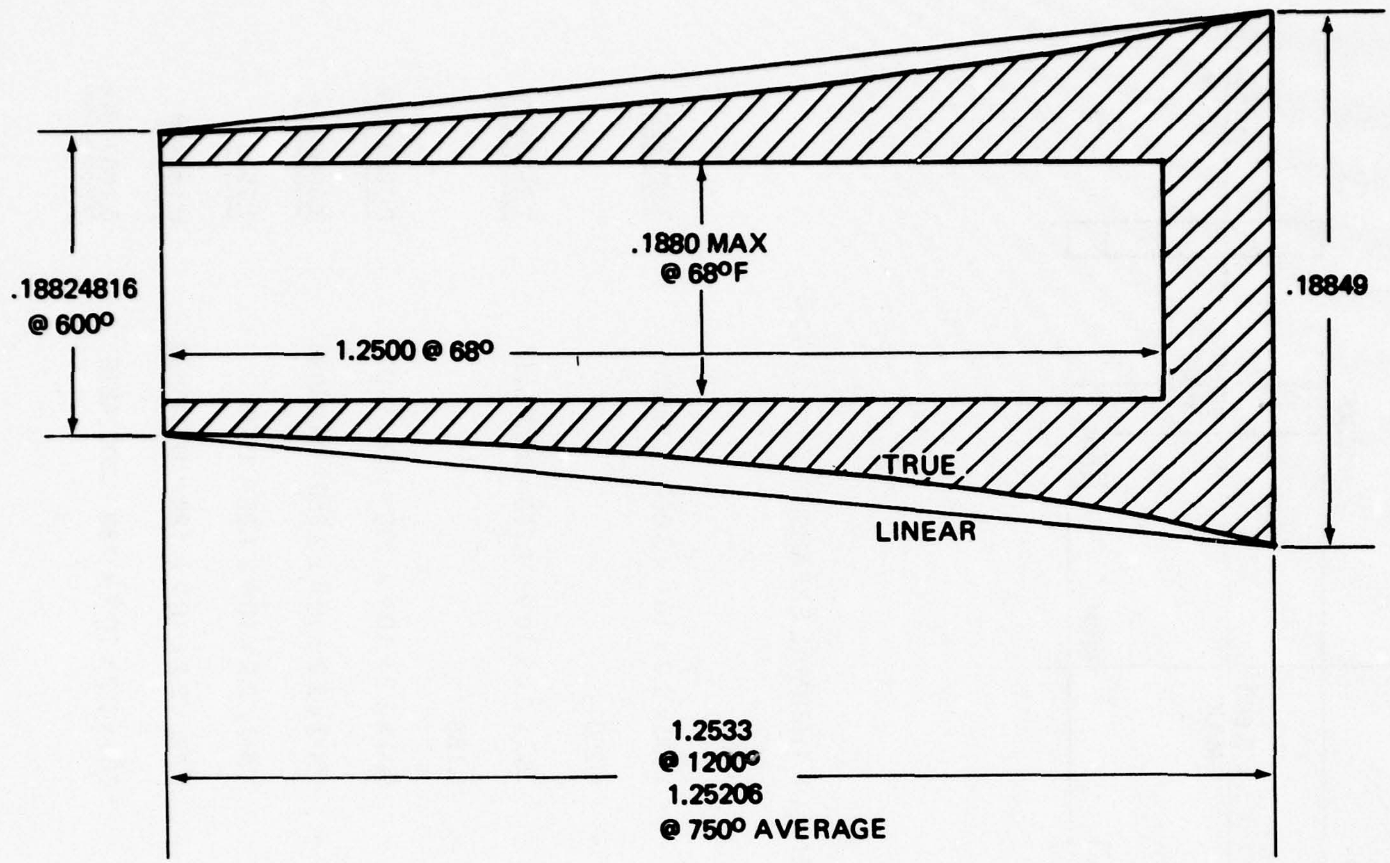
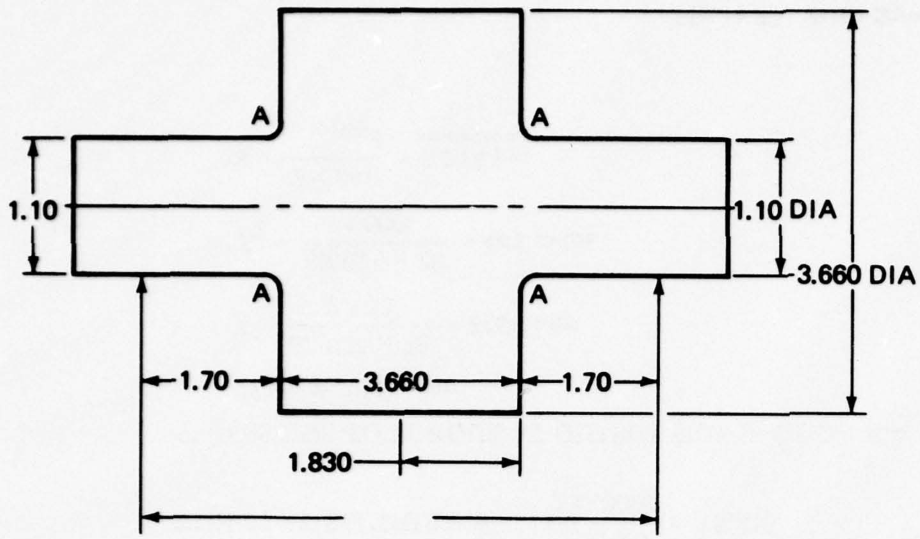
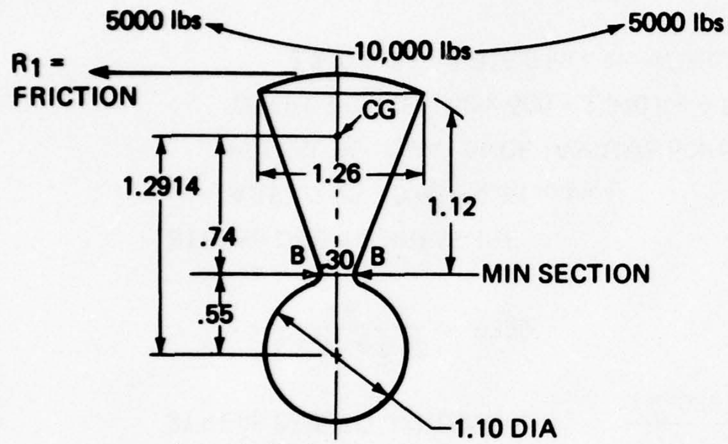


Figure 23. Vane Thermal Expansion





$$\text{AREA} = \frac{(.3 + 1.26)\ 1.12}{2} = .8736$$

VOL = .8736 x 3.66 = 2.882 CU INCH

WEIGHT = 2.882 x .283 = .81 lbs

SHAFT DIA 1.100" DIA

M^T OF INERTIA $.049 \times (1.1)^4 = .07174$

SECTION MOD $.098(1.1)^3 = .1304$

ASSUMED: NO BENDING ON 3.66 LENGTH
DUE TO ROTOR PIES

L = 1.70 + 1.70 = 3.40

MAX DEFLECTION AT LOAD

$$\frac{10{,}000 \times (3.4)^3}{48 \times 30 \times (10)^6 \times .07174} = 0.0038''$$

MAX STRESS AT SECTIONS A-A

$$\frac{10{,}000 \times 3.4}{4 \times .1304} = 65{,}185 \text{ psi}$$

PIE SECTION

a) CG LOCATION

$$C = \frac{h(a + 2b)}{3(a + b)} = \frac{1.12(.3 + 2.52)}{3(1.12 + .30)} = \frac{3.15}{4.26} = .74$$

CG FROM CL = 1.2914

SECTION B-B AREA = .30 x 2.66 = .798 SQ INCH

CENTRIFUGAL FORCE @ 4000 rpm

$F = .000028416 \times 1.2914 \times (4000)^2 \times .81 = 4790$ lbs FORCE

Figure 24. Shaft Stress

STRESS DUE TO CENTRIFUGAL FORCE AT BASE OF PIE — 6,002 psi

FRICTION FORCE: .188 x 3.66 = .68 sq inch x 1,000 psi x .08 = 55 lbs

MT ARM 1.83 - 55 = 1.28 BENDING MT 55 x 1.28 = 70.4 in. lbs

STRESS DUE TO BENDING MT $\dfrac{70.4}{2 \times .0399}$ — -822 psi

$$z = \frac{(.30)^2 \times 2.66}{6} = .0399$$

STRESS DUE TO PRESSURE

AREA 1.28 x 3.66 = 4.68 sq inch

PRESSURE IMBALANCE (ASSUME 500 psi)

TOTAL FORCE 4.68 x 500 = 2,340 lbs AT CENTROID

2,340 x .56 = 1,310.0 inch-lbs MOMENT

STRESS AT SECTION B-B $\dfrac{1,310.0}{2 \times .0399} = 16,416$ — +16,416 psi

STRESS DUE TO TORQUE AT OUTPUT SIDE SECTION A-A

28 hp at 2,100 rpm

$$T = \frac{63,025 \times 28}{2,100} = 840 \text{ in-lbs}$$

$$T_2 = \frac{63,025 \times 28}{4,000} = 441 \text{ in-lbs}$$

$$S = \frac{2 \times 840}{\pi \times .55^3} = \underline{\underline{3,214 \text{ psi}}}$$

TOTAL STRESS AT BASE OF PIE — 17,478 psi

Figure 25. Shaft Stress

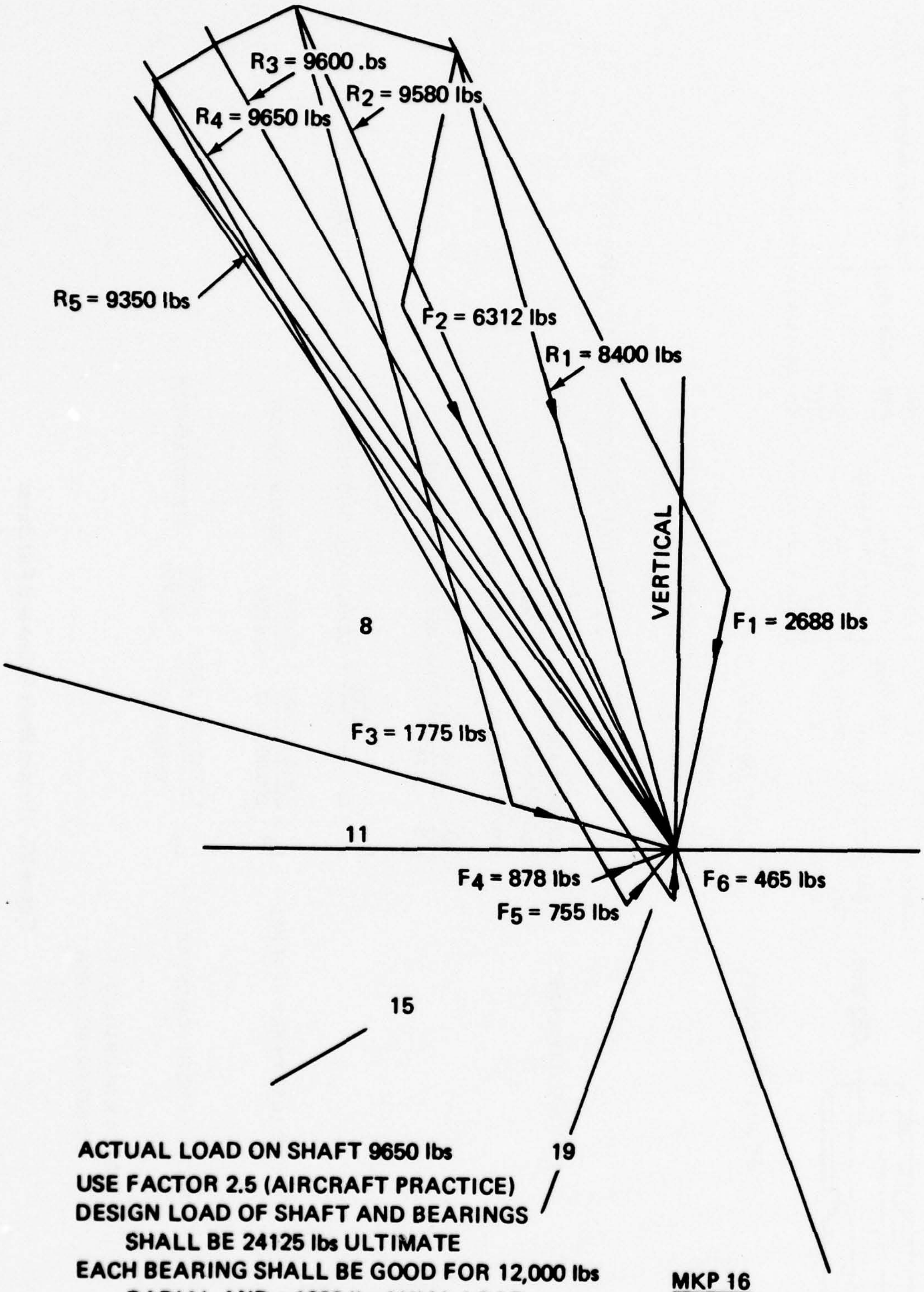
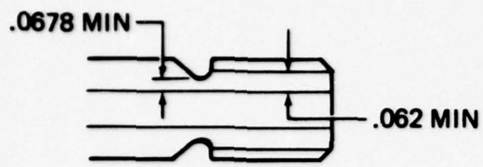


Figure 26. Shaft Loads (25° Inlet)

SPLINE SIZE



ASSUME TORQUE = 71 ft lb

<u>SPLINE F-R-S-F EXTERNAL</u>		PITCH DIA	.8000	FINISH	$63\sqrt{}$
OPERATING TORQUE	852 in.-lbs	MAJOR DIA	.8500 – .8450	SURFACE HARDNESS	R_c 56
MATERIAL		FORM DIA	.7418		
HT TO	125,000 psi	MINOR DIA	.6926 – .6826 = D_o		
DESIGN FACTOR N	3	TOOTH THICKNESS			
PITCH	20/40 30°	ACTUAL	.0700		
NO. OF TEETH	16	EFFECTIVE	.0727		

OTHER DIMENSIONS PER MS-3335(AS) & SAE STANDARD

TUBE WALL THICKNESS:

$$T_U = (T_o)N = 2556 \text{ in-lbs}$$

$$\frac{T_U}{D_o^{\,3}} = \frac{2556}{.3322} = 7693 \text{ psi, USE 8000 psi CURVE}$$

$$\frac{D_o}{t} = 11 \qquad 5 = \frac{.6926}{11} = .062 \text{ MIN WALL THICKNESS REQ TO CARRY TORQUE}$$

RELIEF WALL THICKNESS:

NOMINAL MINOR DIA	.6826
CLEARANCE	<u>.0040</u>
MIN RELIEF DIA	.6786 DIA

$$\frac{T_U}{D_r^{\,3}} = \frac{2556}{.3124} = 8179 \text{ psi, USE 9000 psi CURVE}$$

$$\frac{D_r}{t} = 10 \qquad t = \frac{.6786}{10} = .06786 \text{ WALL THICKNESS REQ TO CARRY TORQUE}$$

SPLINE LENGTH FOR BEARING:

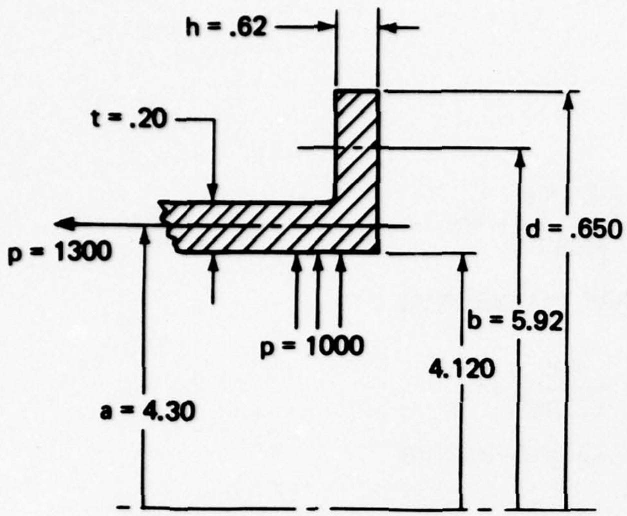
$$L_B = \frac{2.5\,(4 \times 2556)}{200{,}000 \times .64} = \frac{25{,}560}{128{,}000} = .199 \text{ MIN LENGTH}$$

SPLINE LENGTH FOR SHEAR:

$$L_S = \frac{1.2732 \times 4 \times 2.556}{95{,}000 \times .2^2} = \frac{13{,}017}{60{,}800} = .814 \text{ MIN LENGTH}$$

PAD = PER MS-3331(AS) - 2
5.000 BSD BOLT DIA

Figure 27. Output Shaft Spline and Pad Stress



AREA OF CLOSURE $\left(\frac{4.12}{2}\right)^2 \times \pi$ 13.331

MAX PRESSURE 1000 psi

LOAD ON CLOSURE P = 13,000 lbs

$$f = \sqrt{4.30 \times .2} = \boxed{.9273}$$

$$T_1 = \frac{(.2)^3\,[3 \times (4.30)^2 + 5\,(6.50)^2]}{(.62)^3\,[(6.50)^2 - (4.30)^2]} = \frac{2.13376}{5.67697} = \boxed{.3758}$$

$$T_2 = \frac{3.58 \times (.2)^3}{(.62)^3\,[(6.50)^2 - (4.30)^2]}\left[\frac{(6.50)^2}{3}\log_e\frac{5.92}{4.30} + .1\,(5.92)^2 - (4.30)^2\right]$$

$$= \frac{.02864}{5.67697}\,[1.955516619 + 1.65564] = \boxed{.031068}$$

$$V_o = \frac{(.9273)^2 - \frac{(.62)^3}{2 \times .2} \times .3758\ \ [.2 + .2325 \times .9273 \times .3758]\ 1000 - 2 \times .031068\ [.62 + .5377 \times .9273]\ 13{,}000}{1.86 \times .9273 \times .2 + .3758\left[(.62)^2\left[2 + .116 \times \frac{.9273}{.2} \times .3758\right] + 1.6103 \times .9273 \times .62 + .866 \times (.9273)^2\right]} = 942.33$$

$$M_o = \frac{-[1.62)^2 \times .3758 + 1.86 \times .9273 \times .2]\ 942.33 + (.62 \times .031068 \times 13{,}000) - .05 \times .2 \times 1000\left[(.9273)^2 - \frac{(.62)^3}{2 \times .2} \times .3758\right]}{1.5 \times .3758 \times .62 - 3.464 \times .2}$$

$$= \frac{-461.1886 + 250.408 - 4.98}{-.343306} = 599.46 \text{ in-lbs}$$

Figure 28. Stator End Plate Collar Stress

LONG BENDING STRESS IN CYL

$$S_1 = \frac{6 \times 599.46}{(.2)^2} = 89{,}920 \text{ psi}$$

RADIAL BENDING STRESS IN FLANGE

$$S_2 = \frac{6}{.62} \quad 599.46 - \frac{1}{2} \times 942.33 \times .62 = 2{,}974.1 \text{ psi}$$

LONG DIRECT STRESS IN CYL

$$S_3 = \frac{13{,}000 + 700 \times \pi \left(\frac{1}{2} \times 4.30 - \frac{1}{2} \times .2\right)^2}{\pi \times 4.30 \times .2} = \frac{22{,}241.78}{2.701} = 8{,}232 \text{ psi}$$

RADIAL DIRECT STRESS INFLANGE

$$S_4 = \frac{942.33}{.62} + 700 = 2{,}219.88 \text{ psi}$$

TANGENTIAL HOOP STRESS IN FLANGE

$$S_5 = \frac{(.62)^2}{4 \times (.2)^3} \times .3758\ (942.33 + .62 \times 700) = 6{,}213 \text{ psi}$$

Figure 29. Stator End Plate Collar Stress

Table 6. Maximum Stress Levels

Part No.	Name	Material	Max Stress Level: Thermal	Max Stress Level: Loads	Ultimate Tensile Stress: RT	Ultimate Tensile Stress: 1,000°F	Ultimate Tensile Stress: 1,400°F
26651-101-11	Rotor	René 41	48 ksi compr	23 ksi blade load	206 ksi	203 ksi	160 ksi
26652-101-11	Stator	Hastelloy C	150 ksi compr	13.7 ksi hoop	110 ksi	94 ksi	63 ksi
26653-101-11	End plate	Hastelloy C	20 ksi circumf	5.5 ksi	110 ksi	94 ksi	63 ksi
26653-101-11							
26685-301-11	Vane			6.5 ksi flexural			

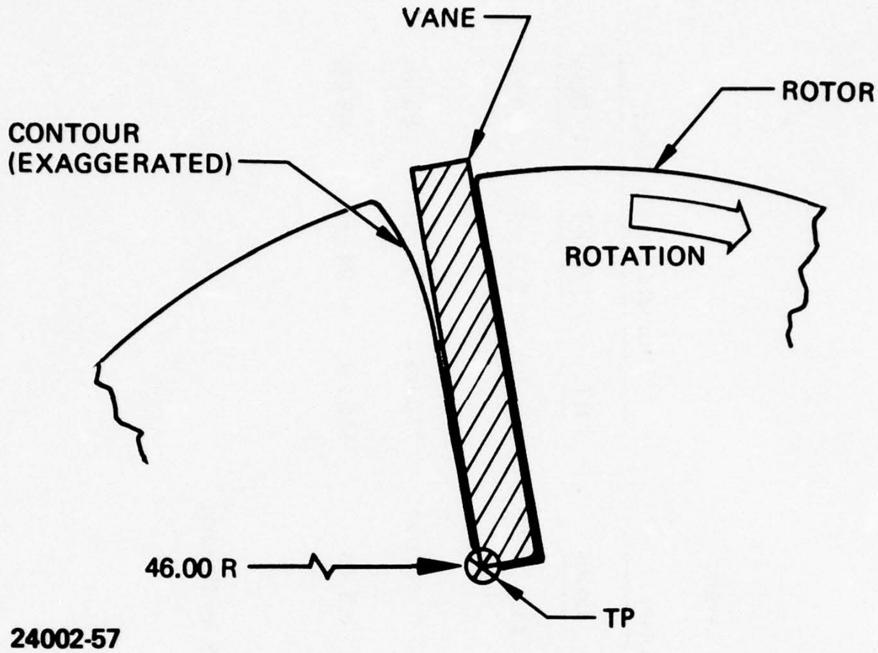


Figure 30. Rotor Vane Slot Contour

4) Bearings and Bearing Support Components – The rotor is positioned and supported with standard MS-rated ball bearings. The fixed bearing (MS 27641-20) is designed to react the axial and radial loads. The bearing at the output end of the rotor shaft (MS 27641-16) is allowed to react against the radial loads while floating in the axial direction. Axial flotation compensates for the differences in thermal expansion between the rotor and stator.

The MS bearings, selected for this application, include integral dust shields that will retain the lubricant that is applied during bearing assembly by the supplier. These bearings are rated for in-service temperatures up to 325°F.

Thermal analyses, as discussed under "Thermal Considerations" below, indicate that the bearing temperature in the starter motor application can be maintained below the 325°F limit under worst-case operating conditions which combine two successive full power, full duration start cycles and hot day surrounds.

Primary bearing heat sources include heat conduction from the end plates, heat conduction from or to the rotor shaft, radiation from the end plates, and convection heating from hot gas leakage. As discussed under "Gas Leakage", heat input to the bearings from the hot gas leak source has been minimized by providing a preferred leak path overboard, up stream of the bearing cavities. The major source of heat in the conduction mode is from the end plates. End plate heat rejection into the bearings has been substantially reduced by the installation of the P/N 26658-104-11 and

26656-102-11 titanium inserts. These inserts increase the thermal resistance between the endcaps and the bearings. The bore in the rotor shaft is also effective in reducing the bearing heat load.

Manufacturing/Assembly Tolerances

Figure 31 (RRC Drawing SK 6013) summarizes all of the manufacturing and assembly tolerances for the starter motor.

Materials of Construction

Figure 32 (RRC Drawing SK 5957) summarizes the materials of construction selected for each component of the starter motor.

THERMAL CONSIDERATIONS

The starter motor has been modeled for computer analysis of the thermal-structural and thermal-performance design verification. These computer programs are described and discussed in Section III of this report. The importance of the thermal analysis is evident from its repeated design influence, as discussed in the foregoing subsections of the structural and mechanical design review.

Figures 33 through 64 are plots of the temperature of the fixed bearing, floating bearing, rotor and vanes as predicted by the thermal-structural model during typical starter operating sequences at the extreme operating ambient temperature conditions of -65°F and +120°F. The node terminology from the computer program is defined in Section III and noted on each figure, where applicable.

Figures 33 through 48 present component temperature versus time predictions for a starter operating sequence at -65°F soak conditions of:

1) A full power, full duration start at -65°F soak conditions, followed by
2) A 1-minute soakback time period simulating a delay between restart attempts, followed by
3) A second full power, full duration restart (assumed successful), followed by
4) A 15-minute soakback period which is shown to be sufficient to assess the peak temperatures in each of the four components.

Figures 49 through 64 are plots of the predicted temperatures of the same starter motor components during the same sequence of opeation at an ambient temperature of +120°F. It is noted that the time required to start the turbine is 12 seconds at -65°F, and 7 seconds at +120°F.

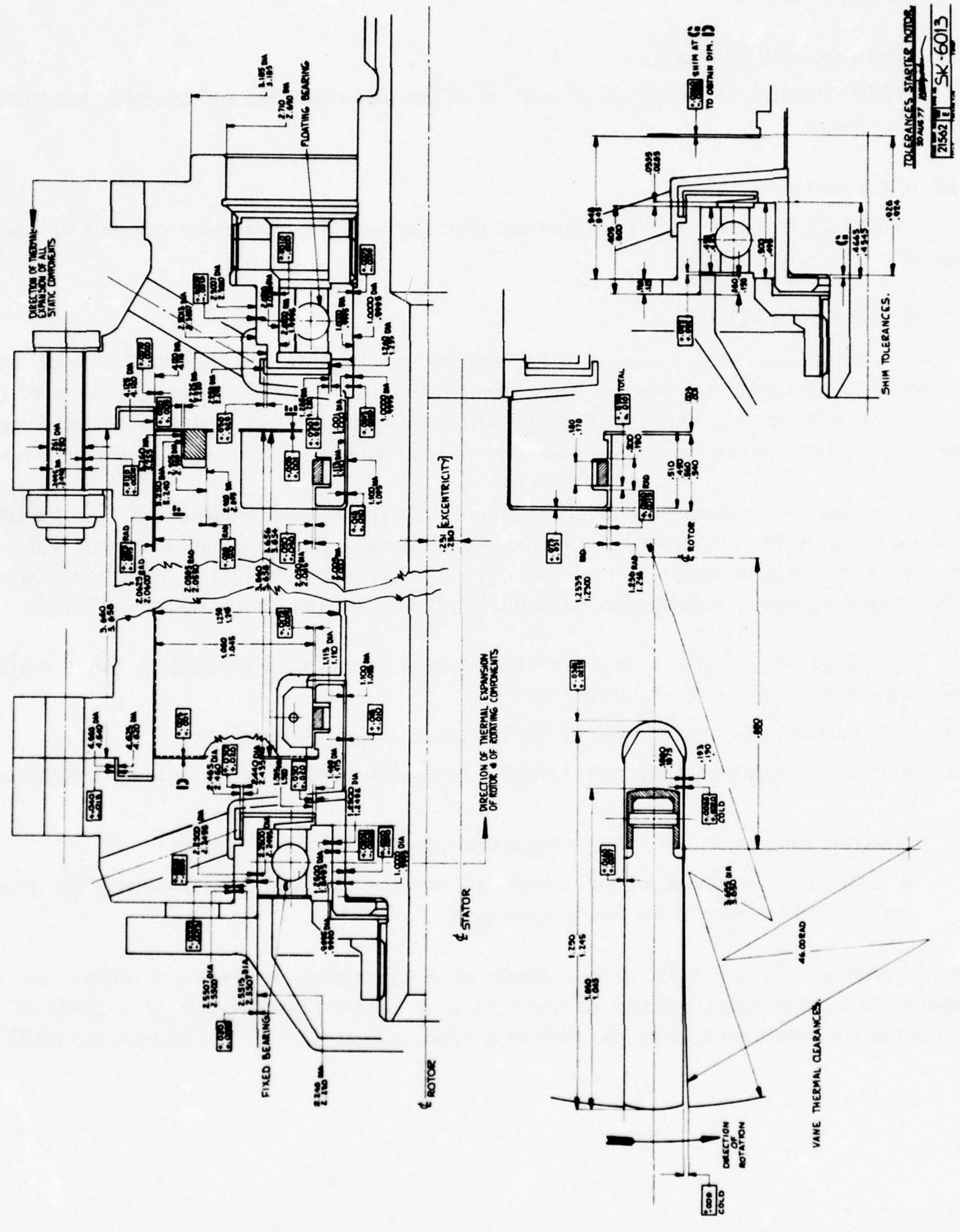


Figure 31. Tolerances Starter Motor

	PART NUMBER	PART NAME	MATERIAL PROTOTYPE	MATERIAL PRODUCTION	WEIGHT PROTO.	WEIGHT PROD.	CORROSION RESISTANCE	REMARKS
1	26651-101-11	ROTOR	RENE 41 BAR PER AMS5713		8.8 LBS	9.1 LBS	RENE 41 GOOD	
2	26652-101-11	STATOR	HASTELOY C SAND CASTING PER AMS5389		10.9 LBs	8.6 LBs	STELLITE GOOD	PRODUCTION MATERIAL STELLITE CASTING
3	26653-101-11	END PLATE	HASTELOY C SAND CASTING PER AMS5389		5.3 LBs	4.5 LBs	— " —	— " — " —
4	26654-101-11	END PLATE			7.1 LBS	6.4 LBS	— " —	— " — " —
5	26656-101-11	DEFLECTOR	TITANIUM BAR 6AL-4V PER AMS4928B		.0339 LBs		GOOD	
6	26656-102-11	BEARING SEAT	TITANIUM BAR 6AL-4V PER AMS4928B		.1392 LBs			
7	26656-103-11	NUT	15-5PH CRES BAR PER AMS 5659		.2709 LBs			TITANIUM
8	26656-104-11	RING NUT	15-5PH CRES BAR PER AMS 5659		.2471 LBs			— " —
9	26657-101-11	SPLIT RING	INCONEL X-750 BAR PER AMS5669		.056 LBs			SET OF TWO
10	26657-102-11	SPRING	ELGILOY STRIP .007 × .100 × 1.000		.008 LBs			WEIGHT OF 16 UNITS
11	26657-103-11	LOCK	302 CRES WIRE PER QQ-W-423		.0011 LBs			
12	26657-104-11	LOCK LARGE	302 CRES WIRE PER QQ-W-423		.00249 LBs			
13	26657-105-11	SHIM	302 CRES SHIM LAMINATE		.0013 LBs			
14	26657-106-11	SHIM	302 CRES SHIM LAMINATE		.0034 LBs			
15	26658-101-11	END CAP	15-5PH CRES BAR PER AMS 5659		.5985 LBs			TITANIUM
16	26658-102-11	WASHER	TITANIUM BAR 6AL-4V PER AMS4928B		.0399 LBs			
17	26658-103-11	SPACER	TITANIUM BAR 6AL-4V PER AMS 4928B		.0072 LBs		GOOD	
18	26658-104-11	RETAINER	TITANIUM BAR 6AL-4V PER AMS 4928B		.2959 LBS			
19	26684-301-11	SEAL (SET)	REINFORCED CARBON		.105 LBS			TWO SETS OF EIGHT
20	26685-301-11	VANE ASSY	P-658RCH CARBON		.492 LBs			SET OF EIGHT
21	MS27641-20	BEARING			.22 LBS			POSSIBILITY OF STELLITE 6 BEARING
22	MS27641-26	BEARING			.26 LBS			POSSIBILITY OF STELLITE 6 BEARING
23	AND960-416L	WASHER			$\left.\begin{array}{l} \\ \\ \\ \end{array}\right\}$ .375 LBS			
24	VS2627-4-16	BOLT						
25	VS324-B-10B	LOCK NUT						
26	VS324-B-04B	LOCK NUT						
					TOTAL	TOTAL		
					35.35	31.84		
					LBS	LBS		

Figure 32. Materials Used for APU Hydrazine Starter

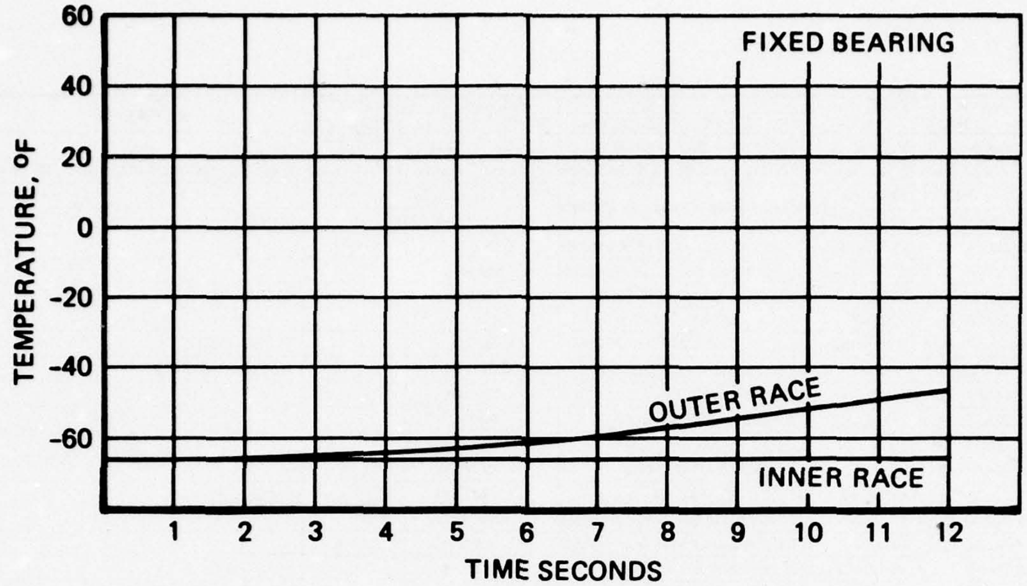


Figure 33. First 12-Second Firing at -65°F

24002-58

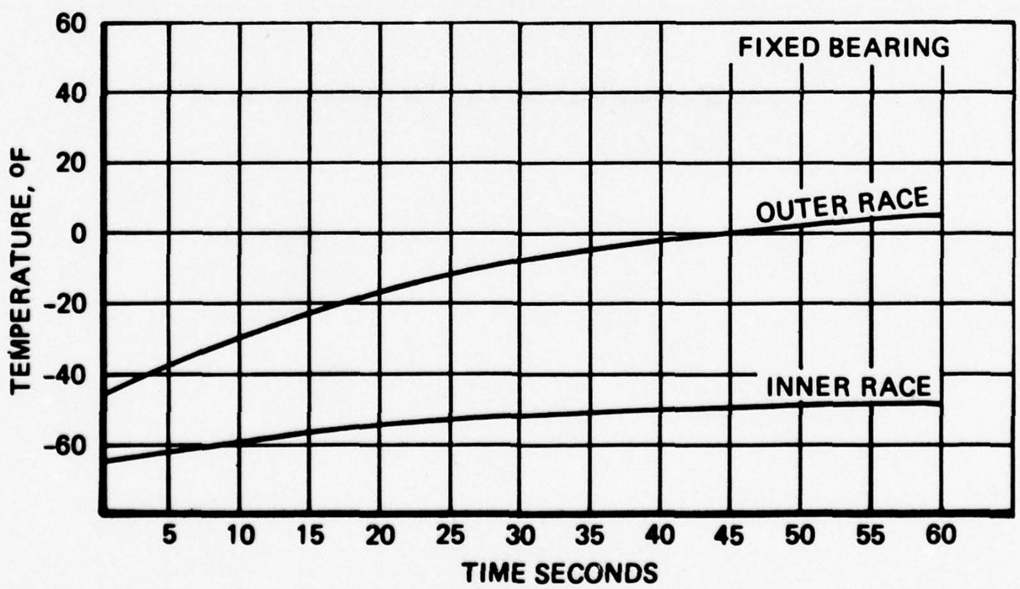


Figure 34. 1 Minute Soakback at -65°F

24002-59

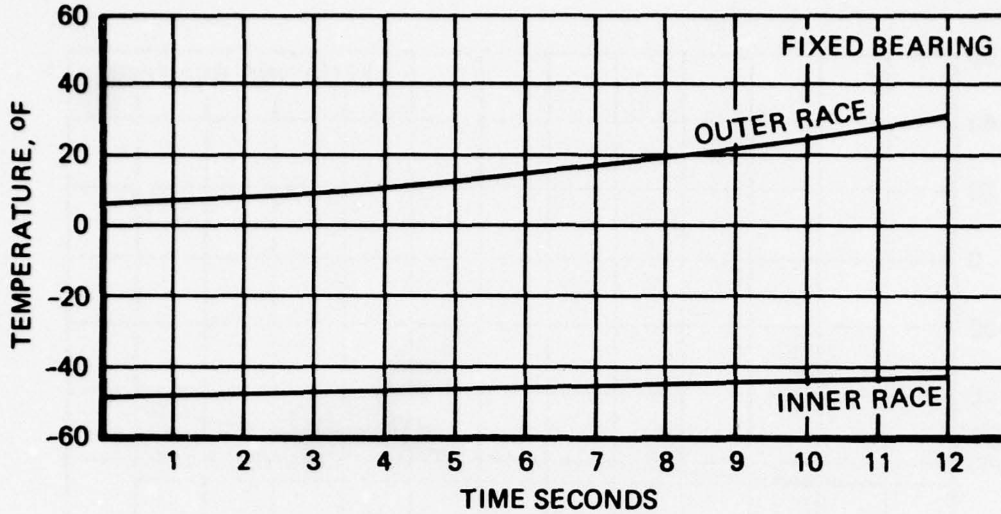


Figure 35. Second 12-Second Firing at -65°F

24002-60

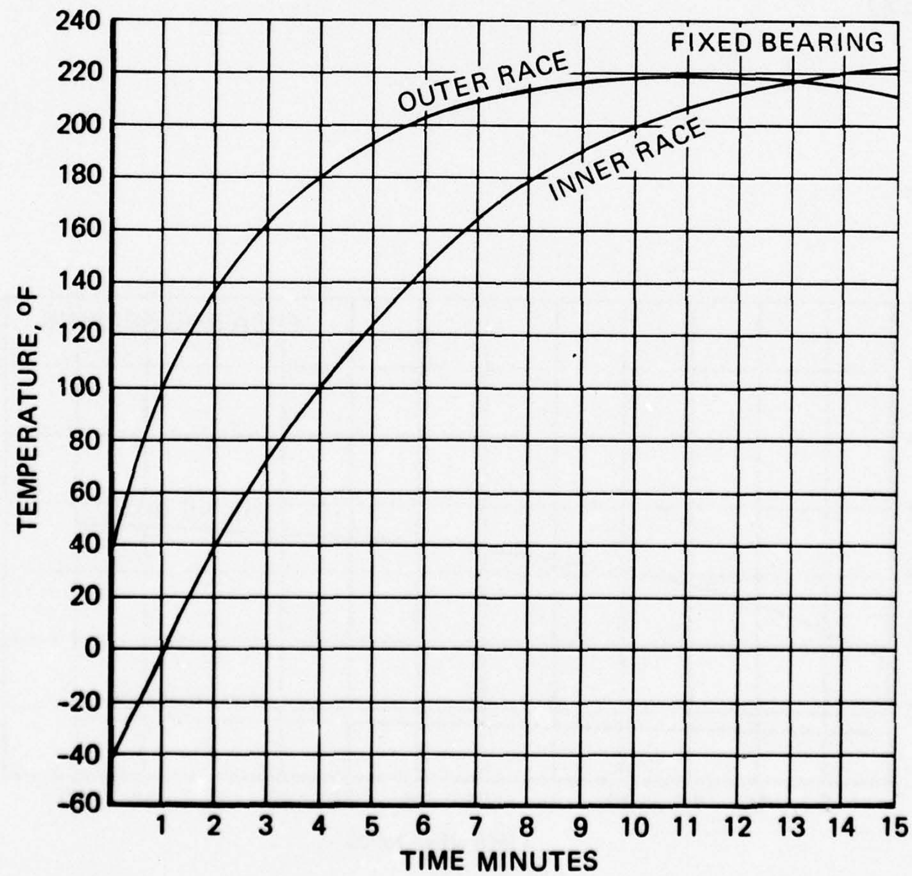


Figure 36. 15 Minute Soakback at -65°F

24002-61

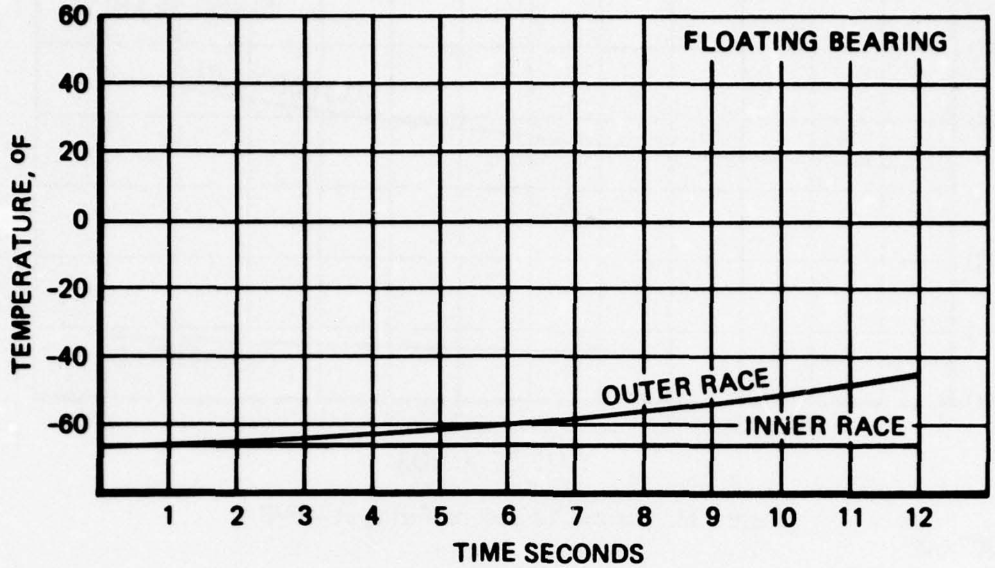


Figure 37. First 12-Second Firing at -65°F

24002-62

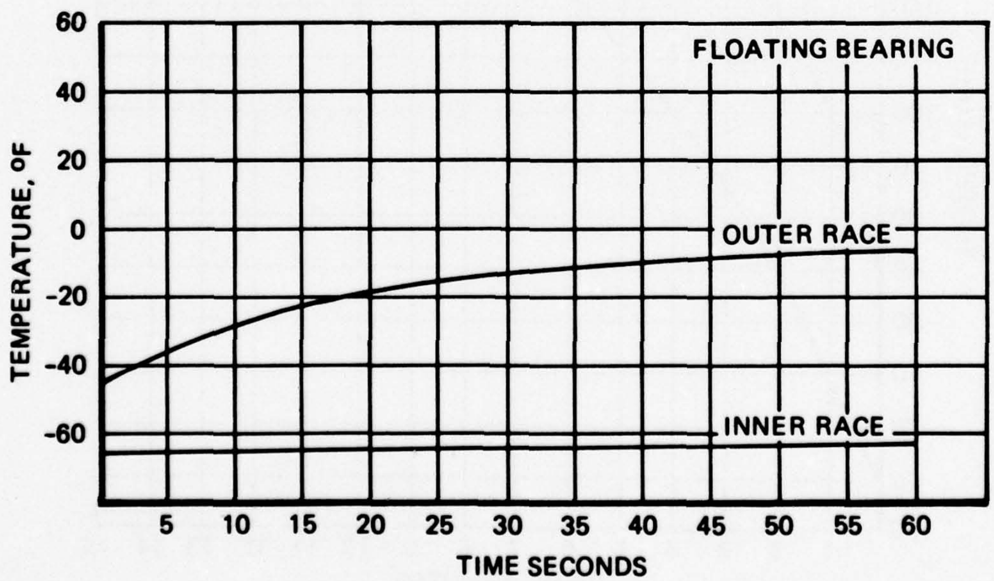


Figure 38. 1 Minute Soakback at -65°F

24002-63

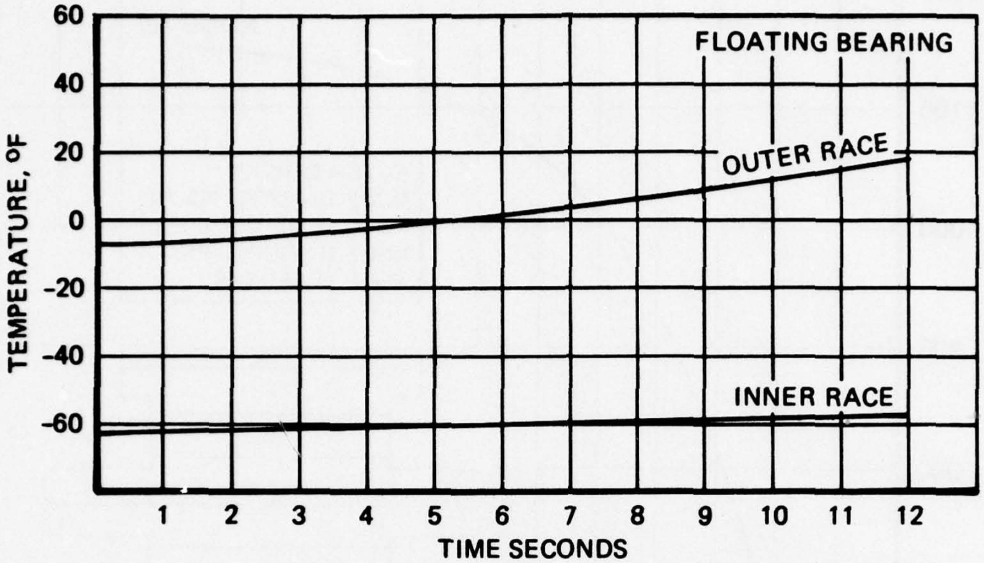


Figure 39. Second 12-Second Firing at -65°F

24002-64

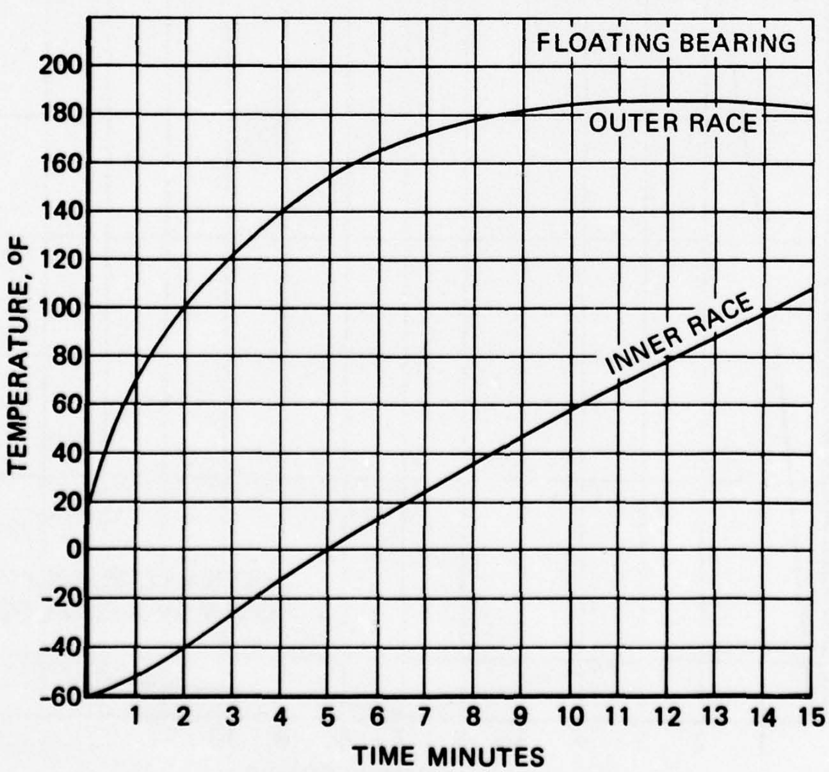


Figure 40. 15 Minute Soakback at -65°F

24002-65

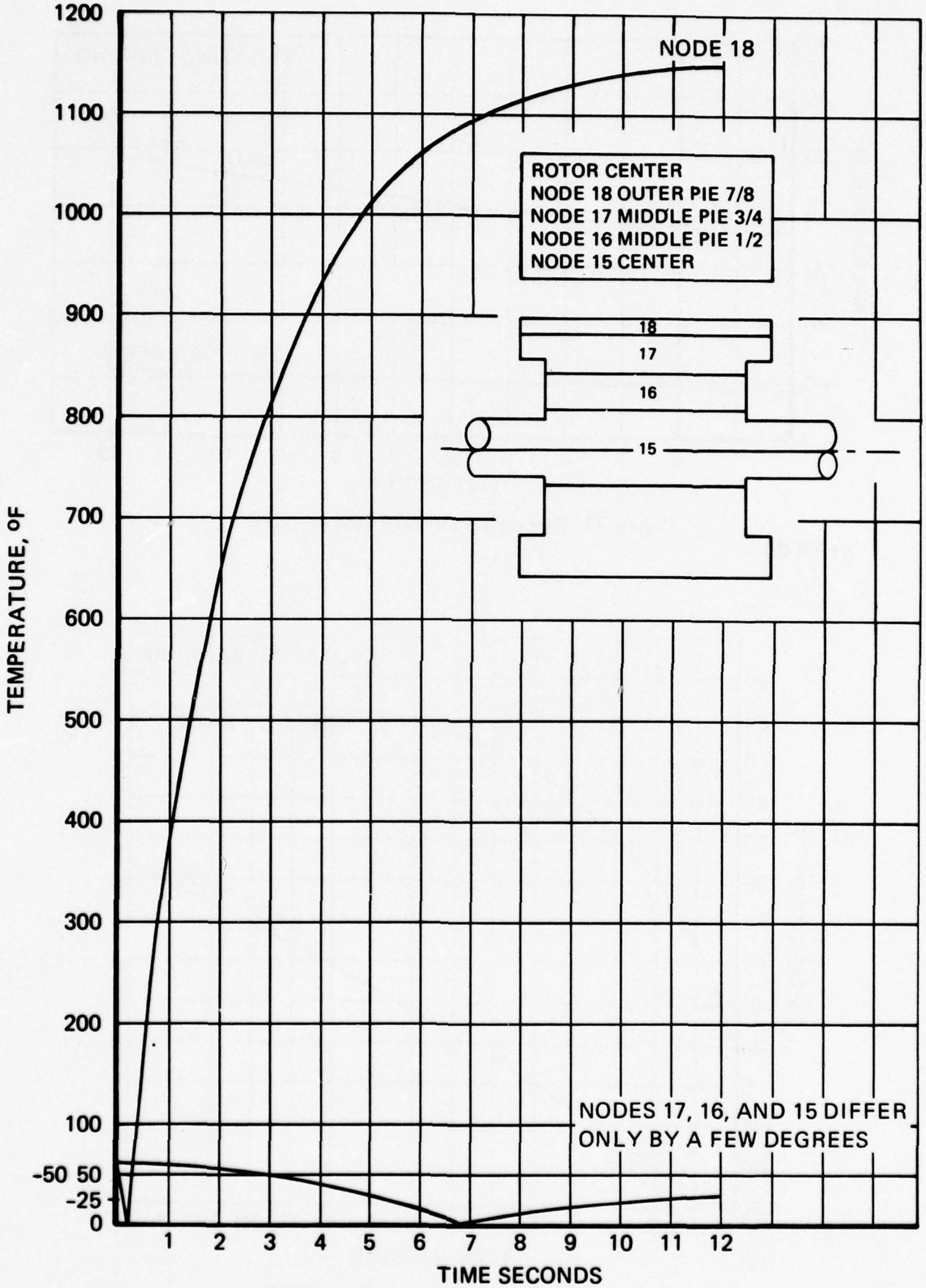


Figure 41. First 12-Second Firing at -65°F

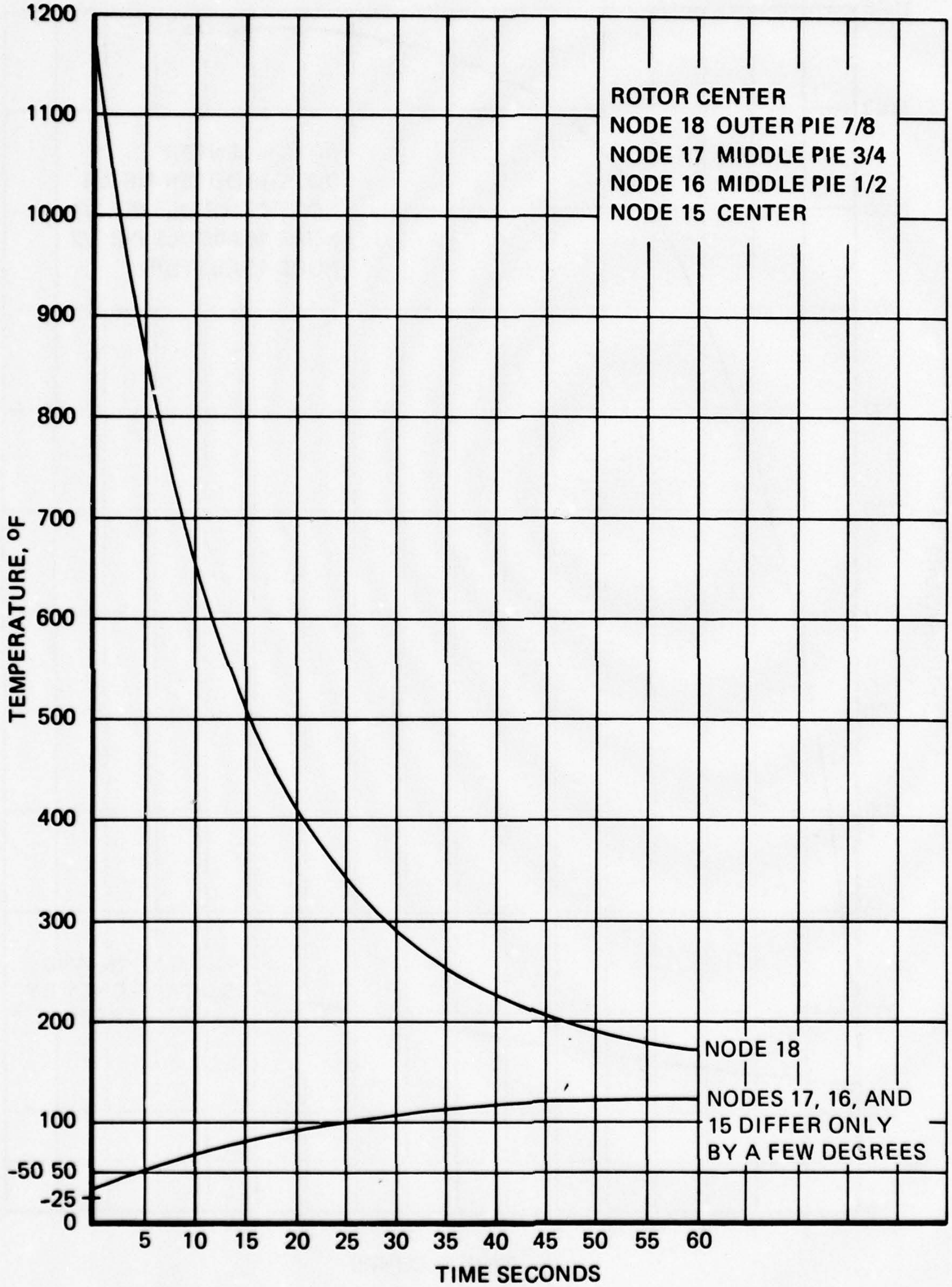


Figure 42. 1 Minute Soakback at -65°F

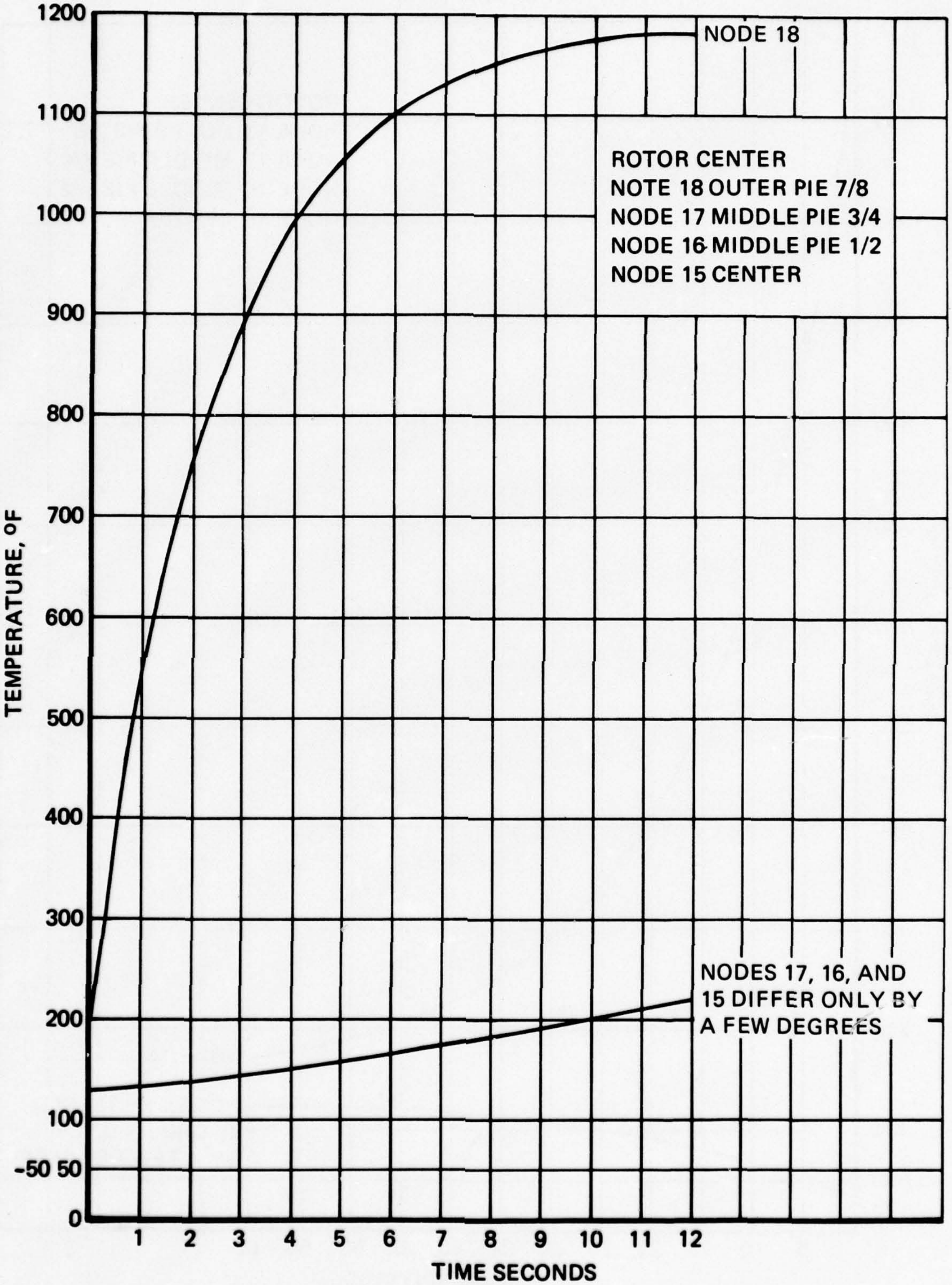


Figure 43. Second 12-Second Firing at -65°F

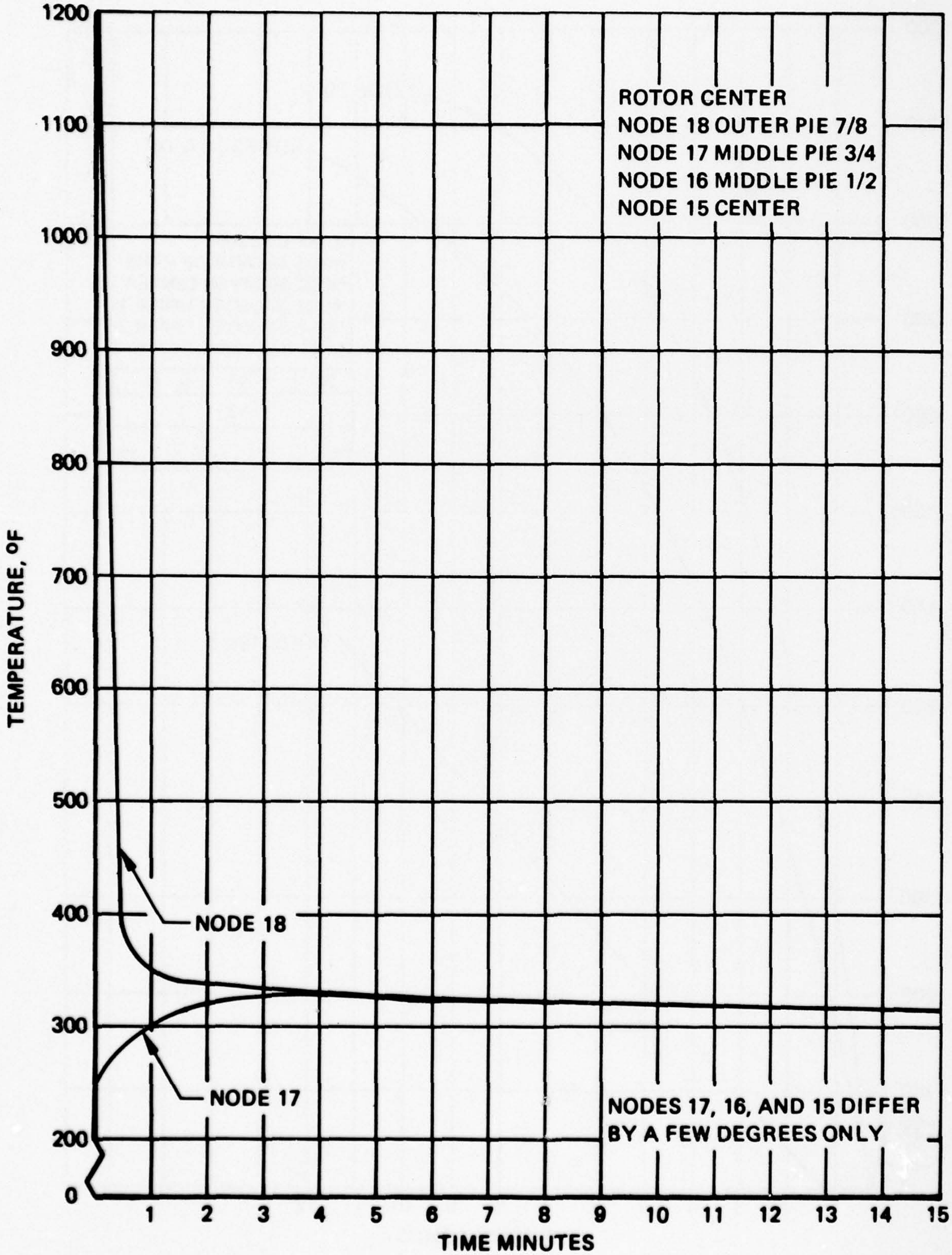


Figure 44. 15 Minute Soakback at -65°F

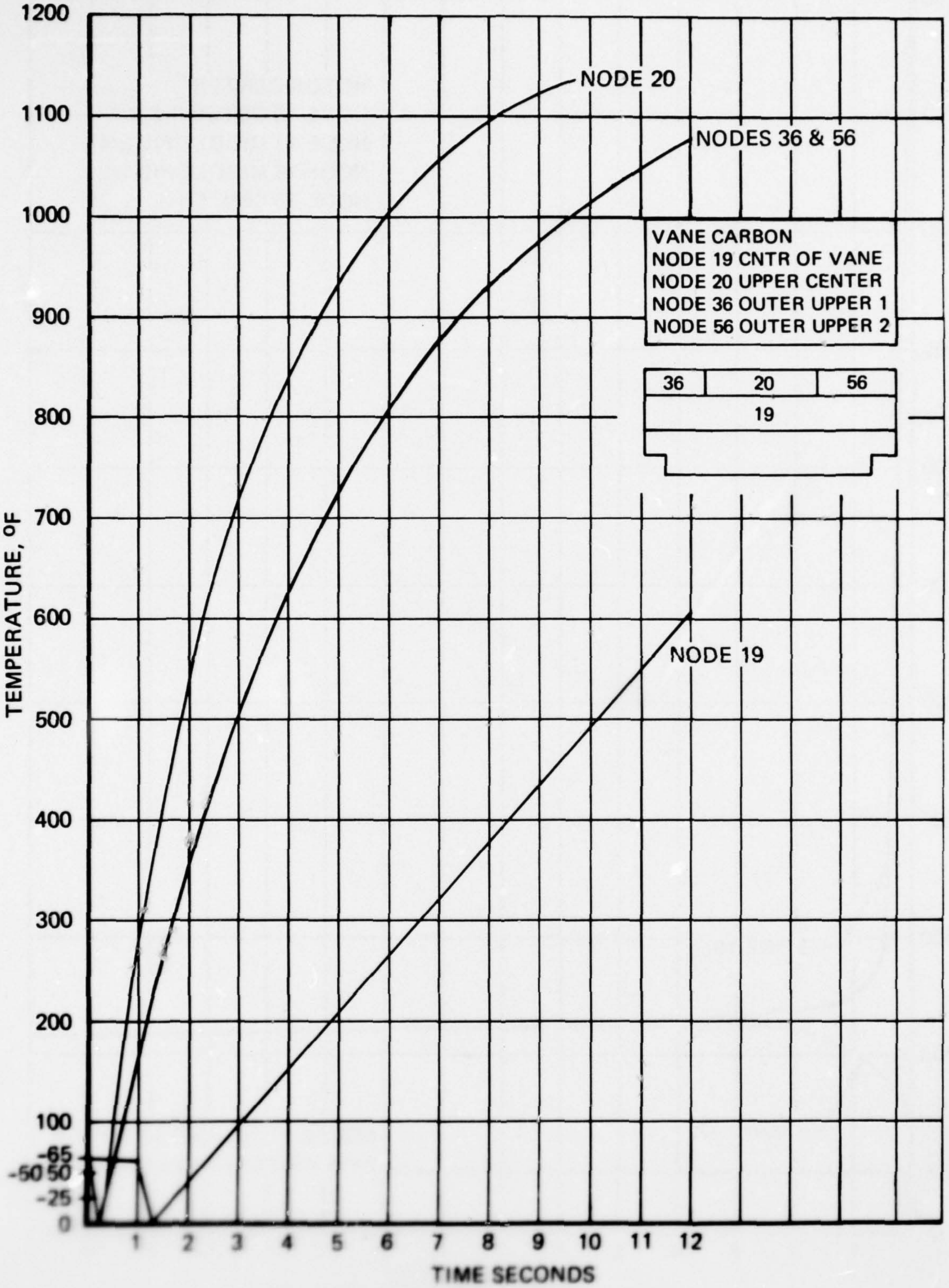


Figure 45. First 12-Second Firing at -65°F

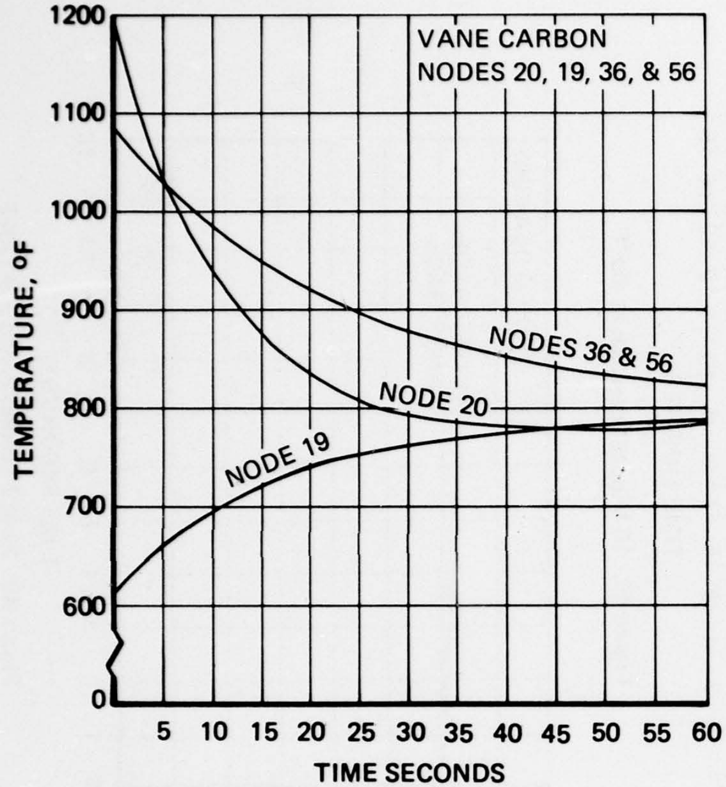


Figure 46. 1 Minute Soakback at -65°F

24002-71

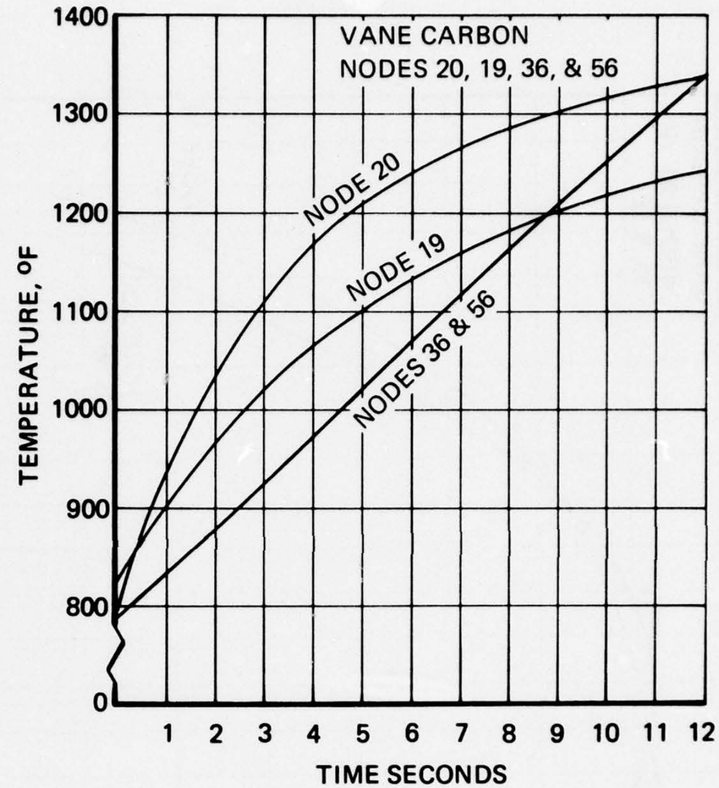
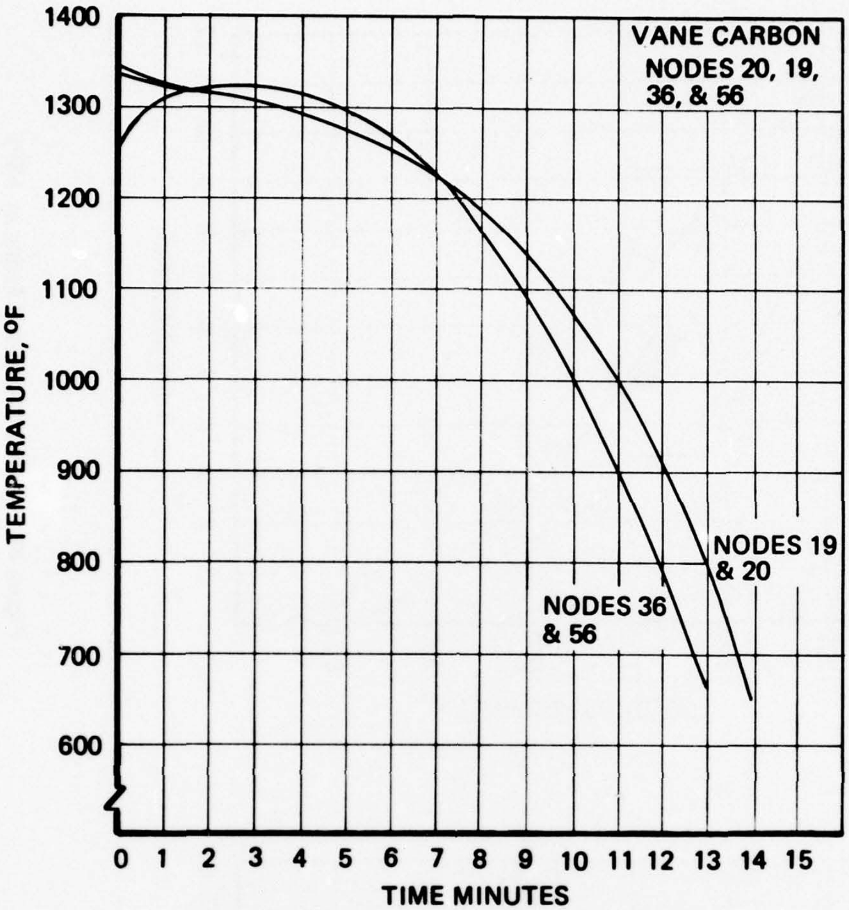


Figure 47. Second 12-Second Firing at -65°F

24002-72



24002-73

Figure 48. 15 Minute Soakback at -65°F

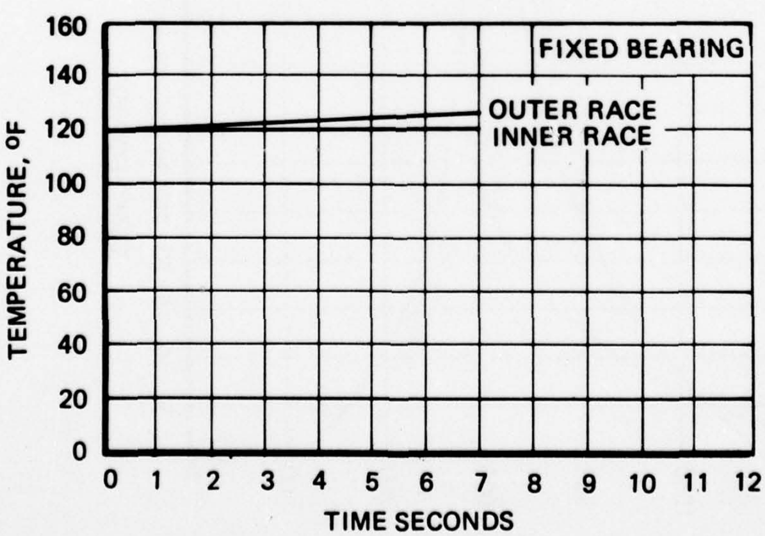
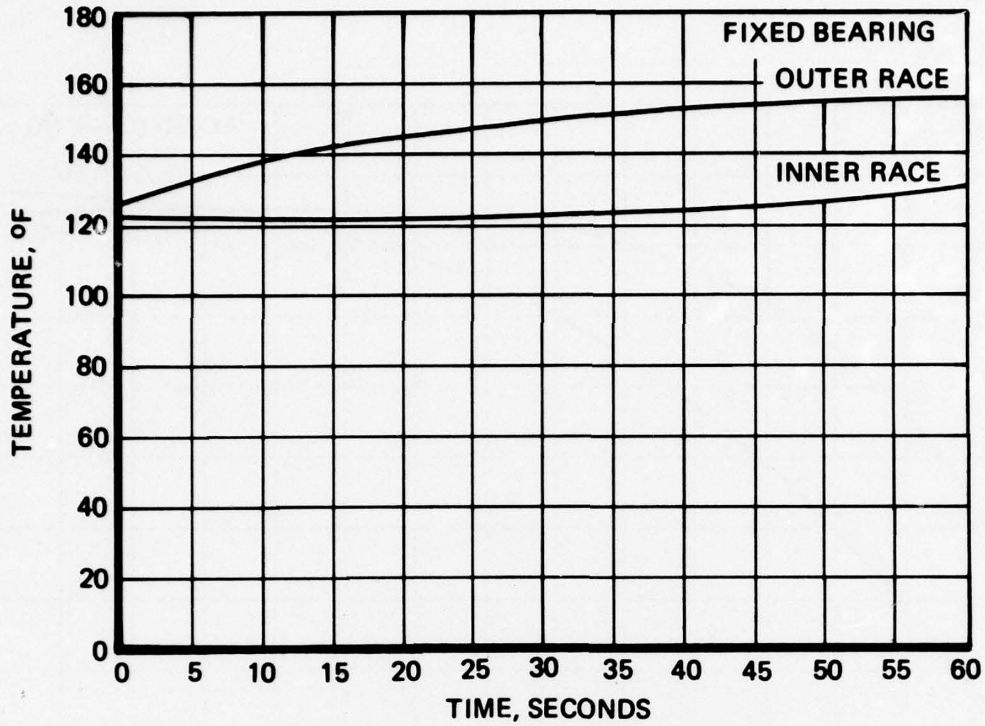


Figure 49. First 7-Second Firing at +120°F

24002-74



24002-75

Figure 50. 1 Minute Soakback at +120°F

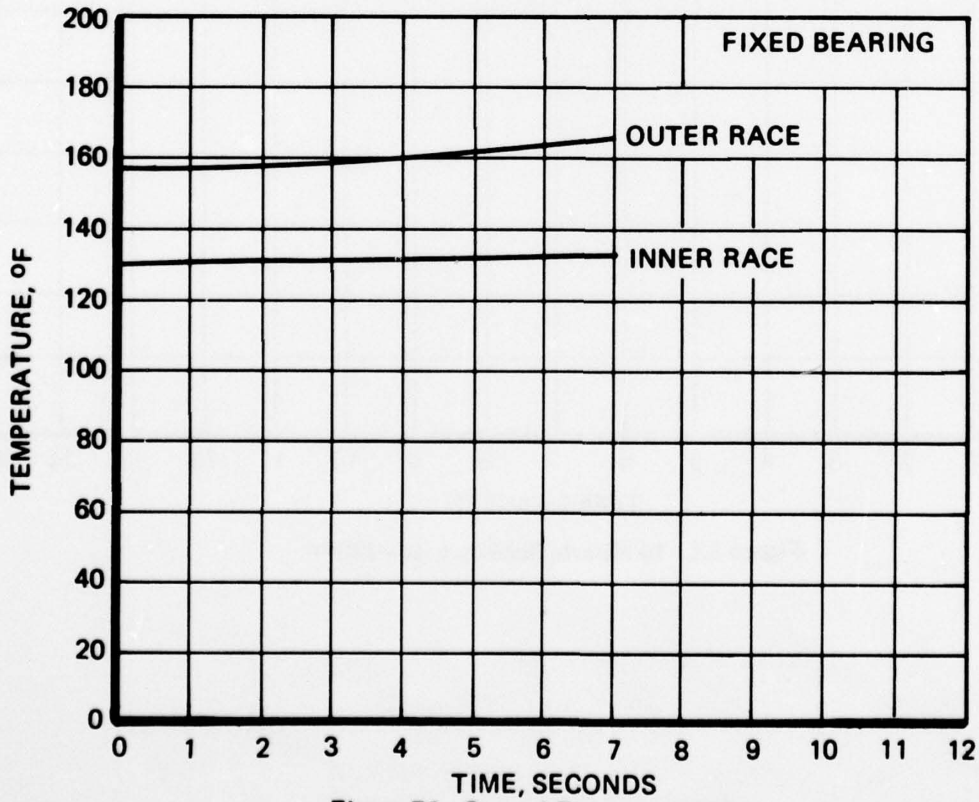


Figure 51. Second Firing at +120°F

24002-76

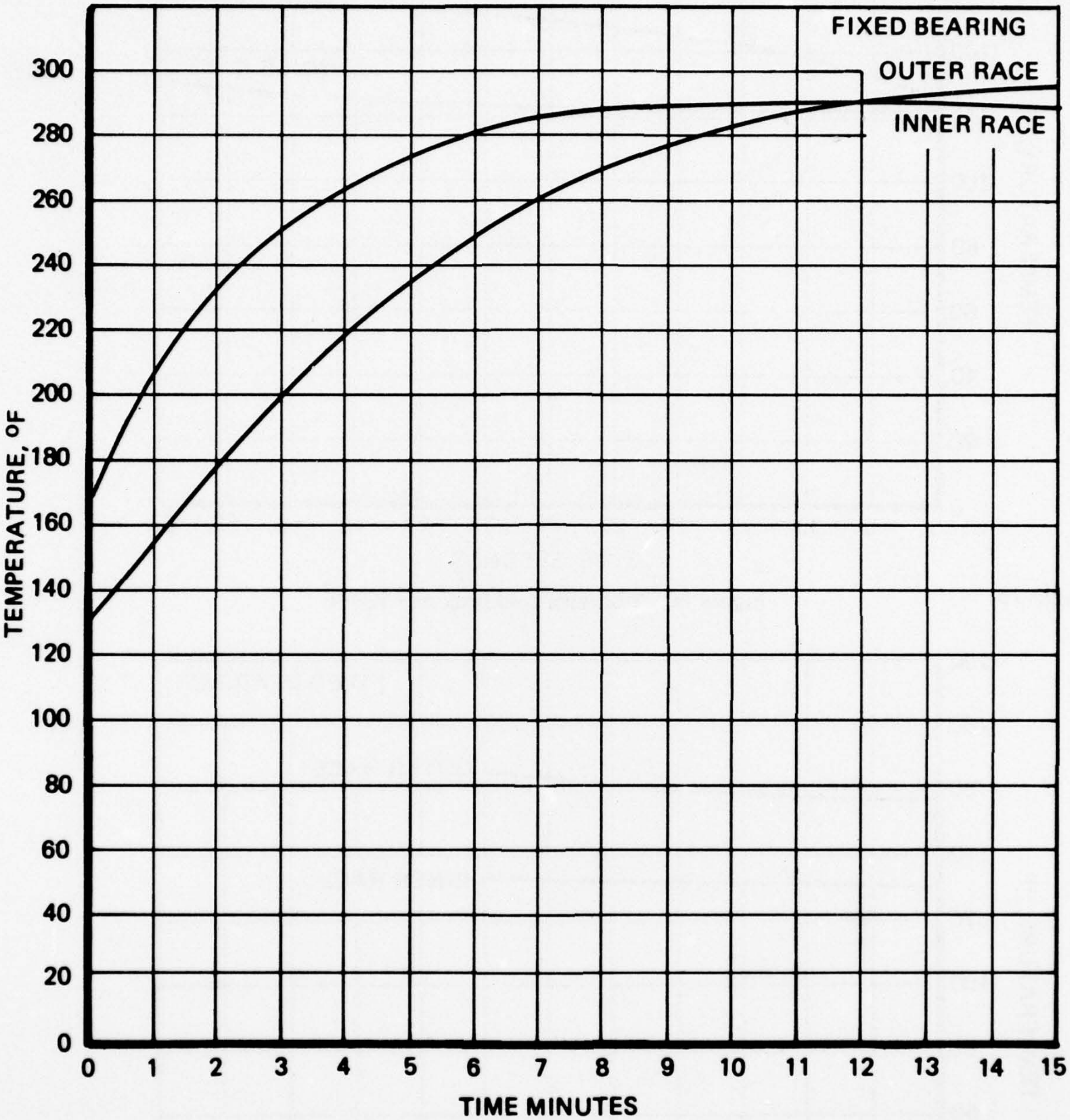
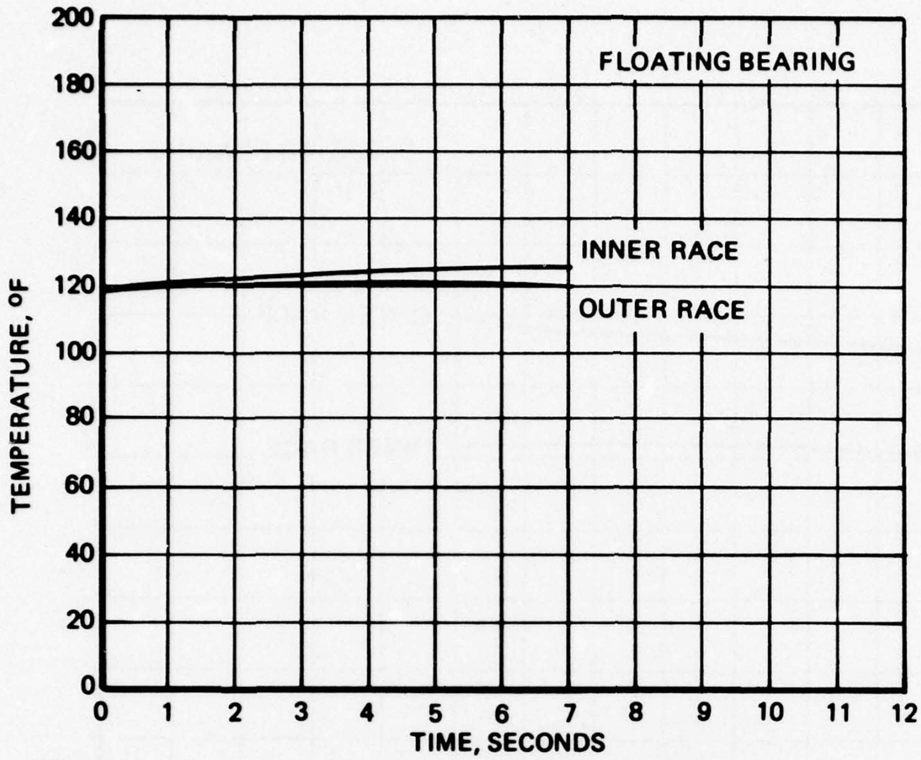
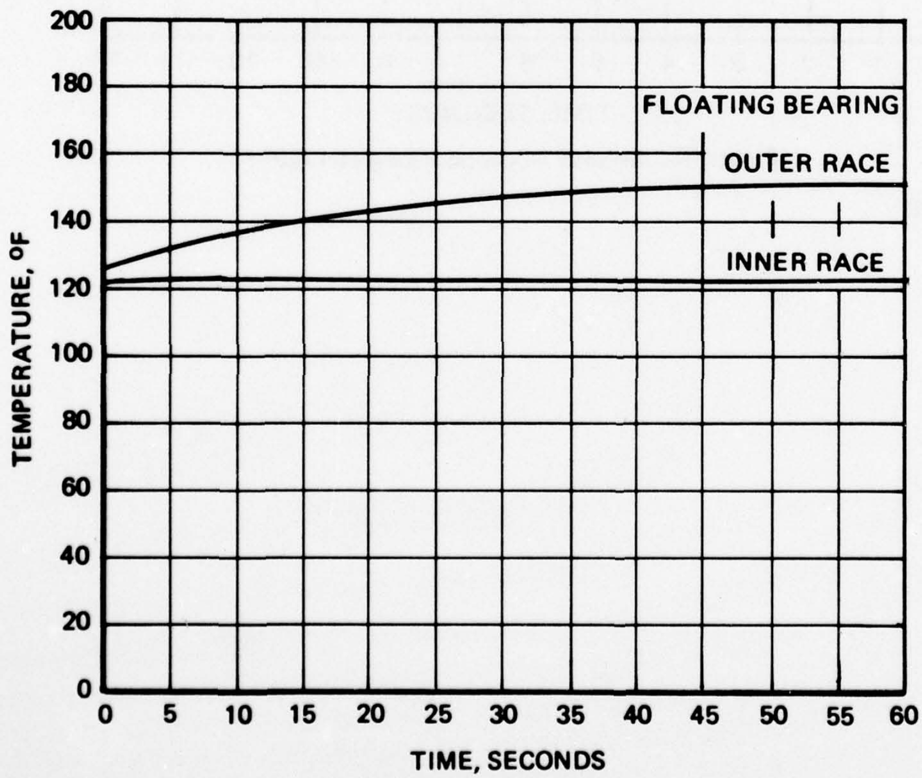


Figure 52. 15 Minute Soakback at +120°F



24002-78

Figure 53. First 7-Second Firing at +120°F



24002-79

Figure 54. 1-Minute Soakback at 120°F

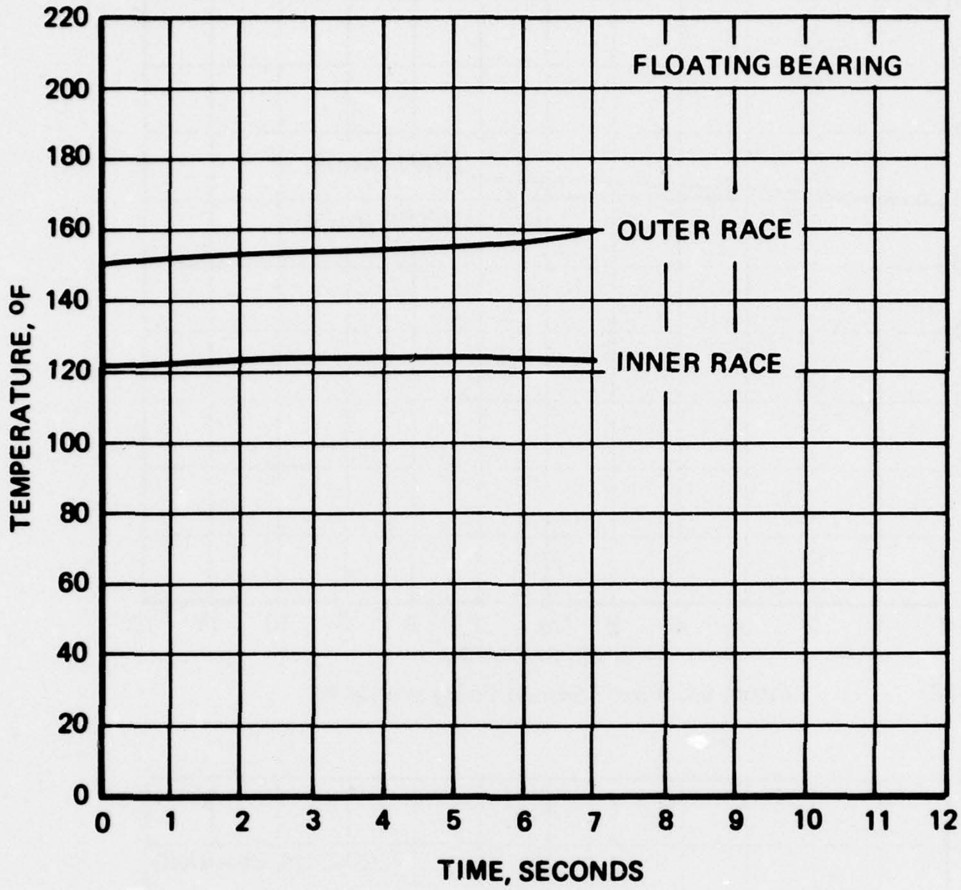


Figure 55. Second 7-Second Firing at +120°F

24002-80

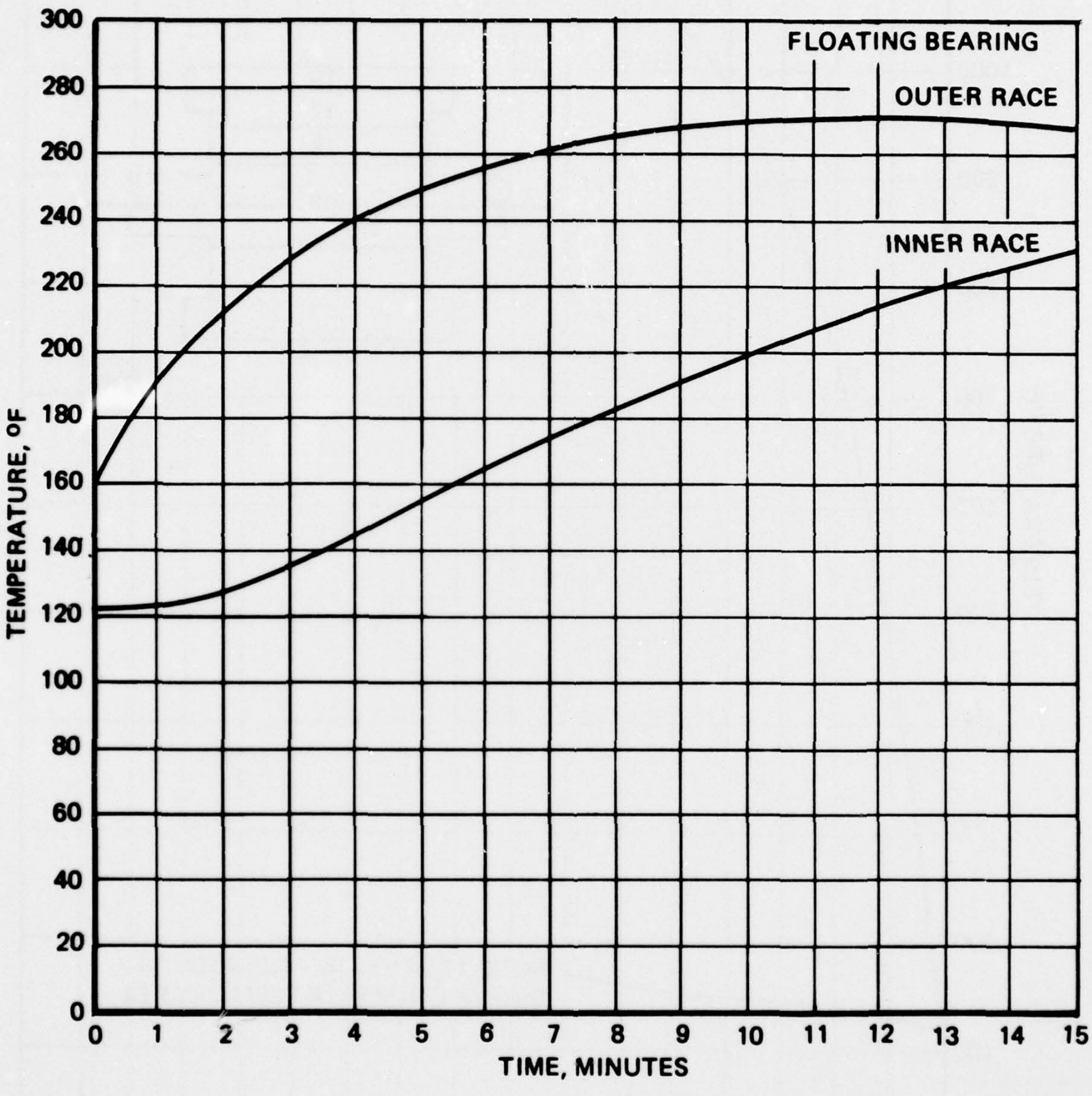


Figure 56. Fifteen-Minute Soakback at +120°F

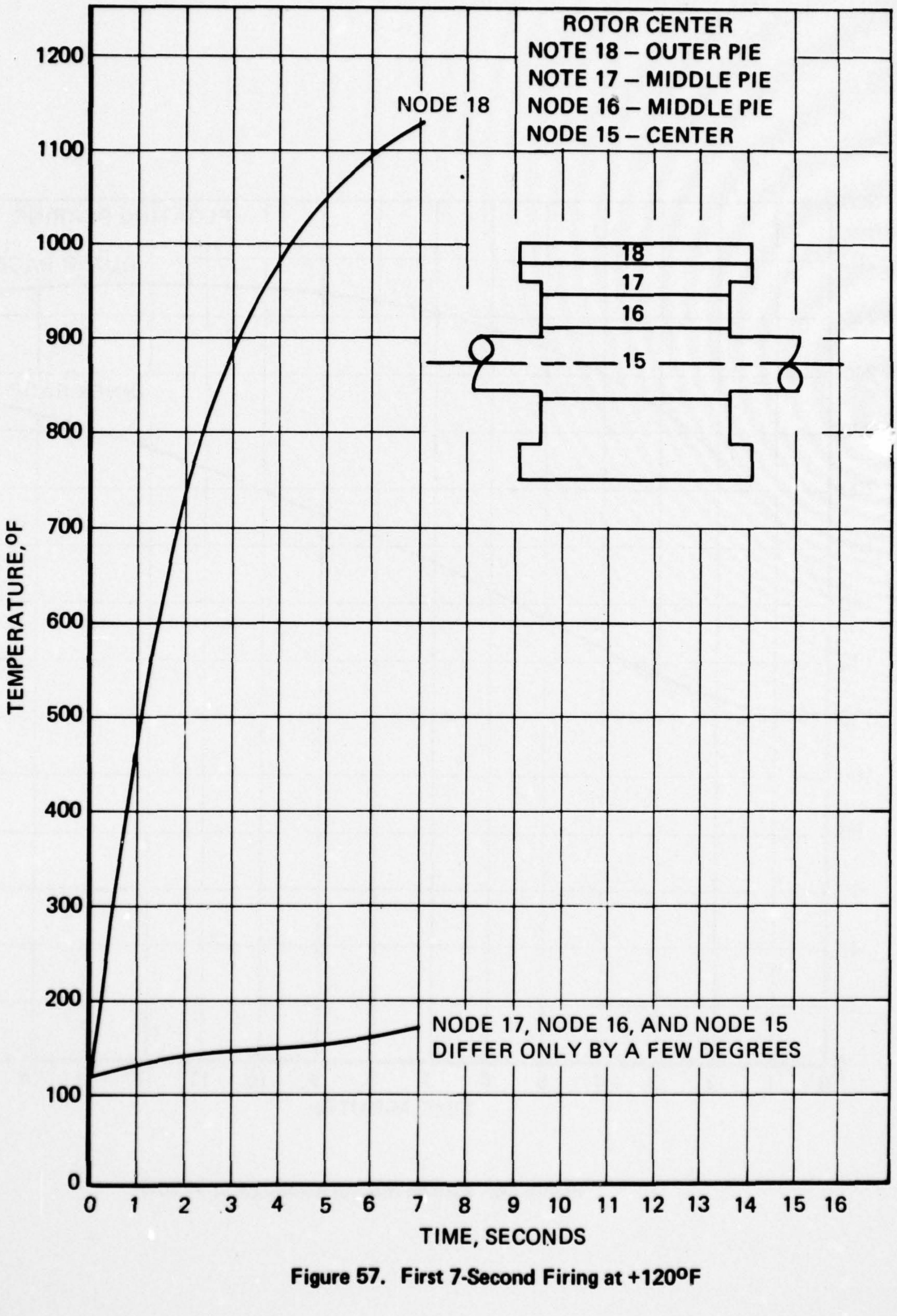


Figure 57. First 7-Second Firing at +120°F

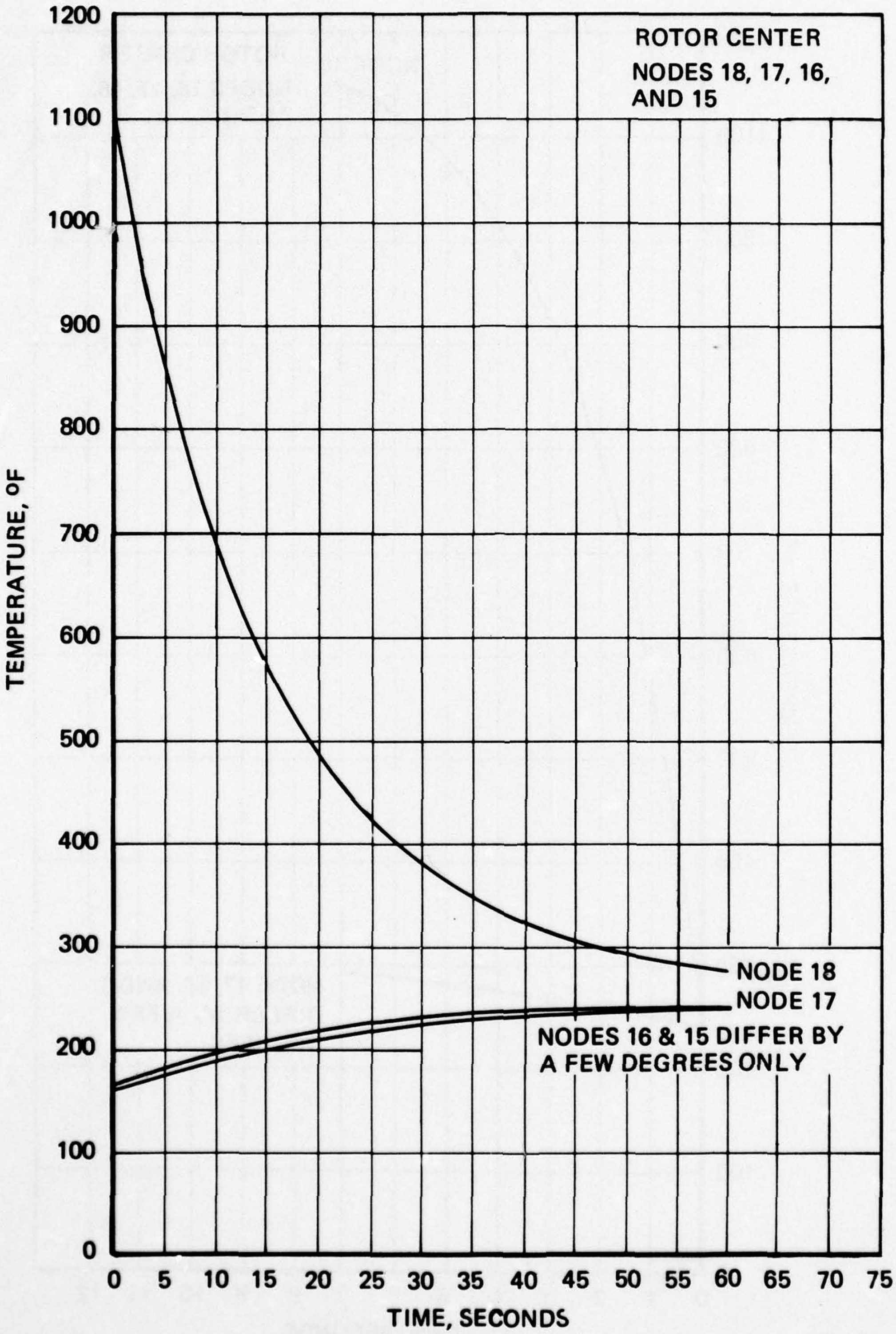


Figure 58. One-Minute Soakback at +120°F

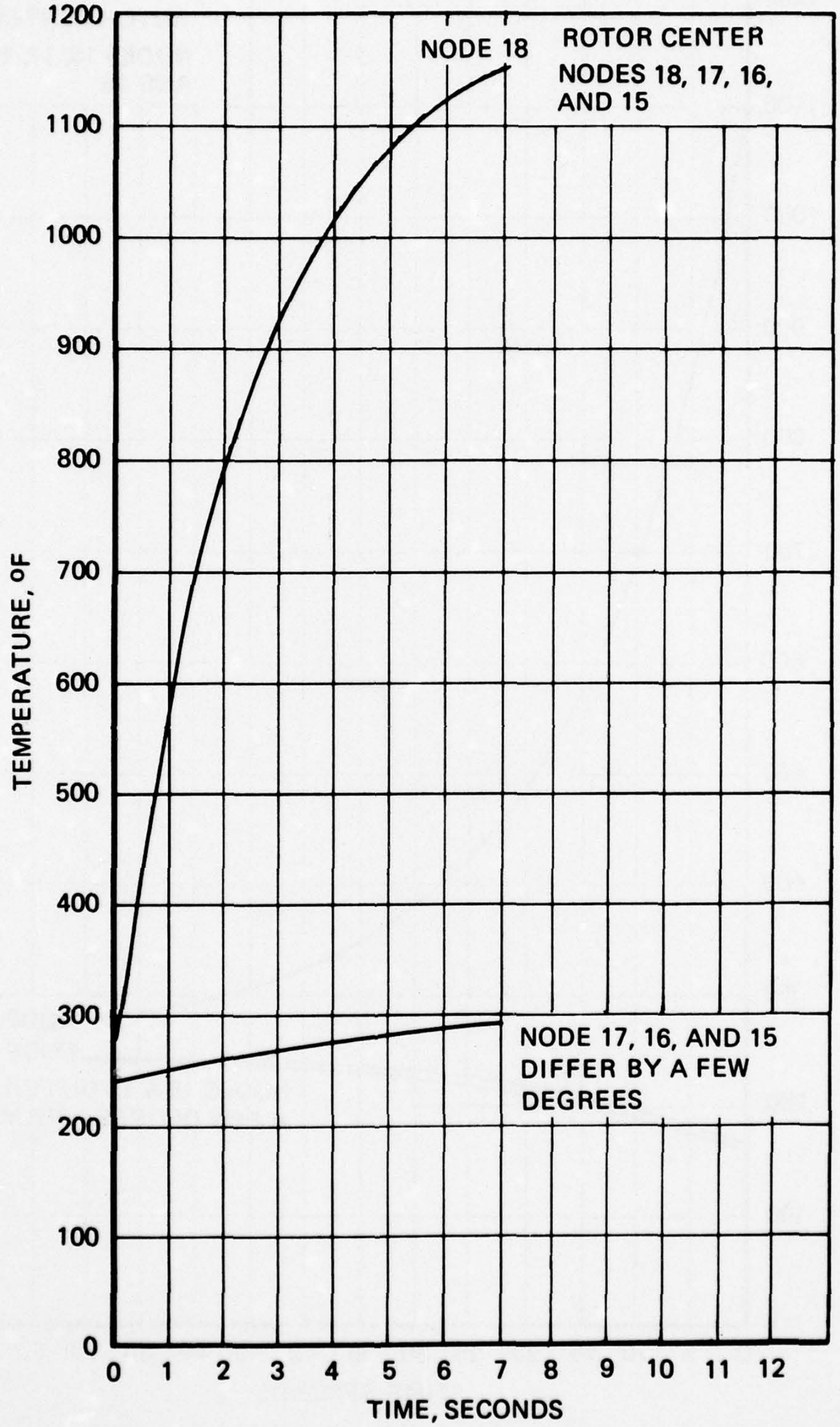


Figure 59. Second 7-Second Firing at 120°F

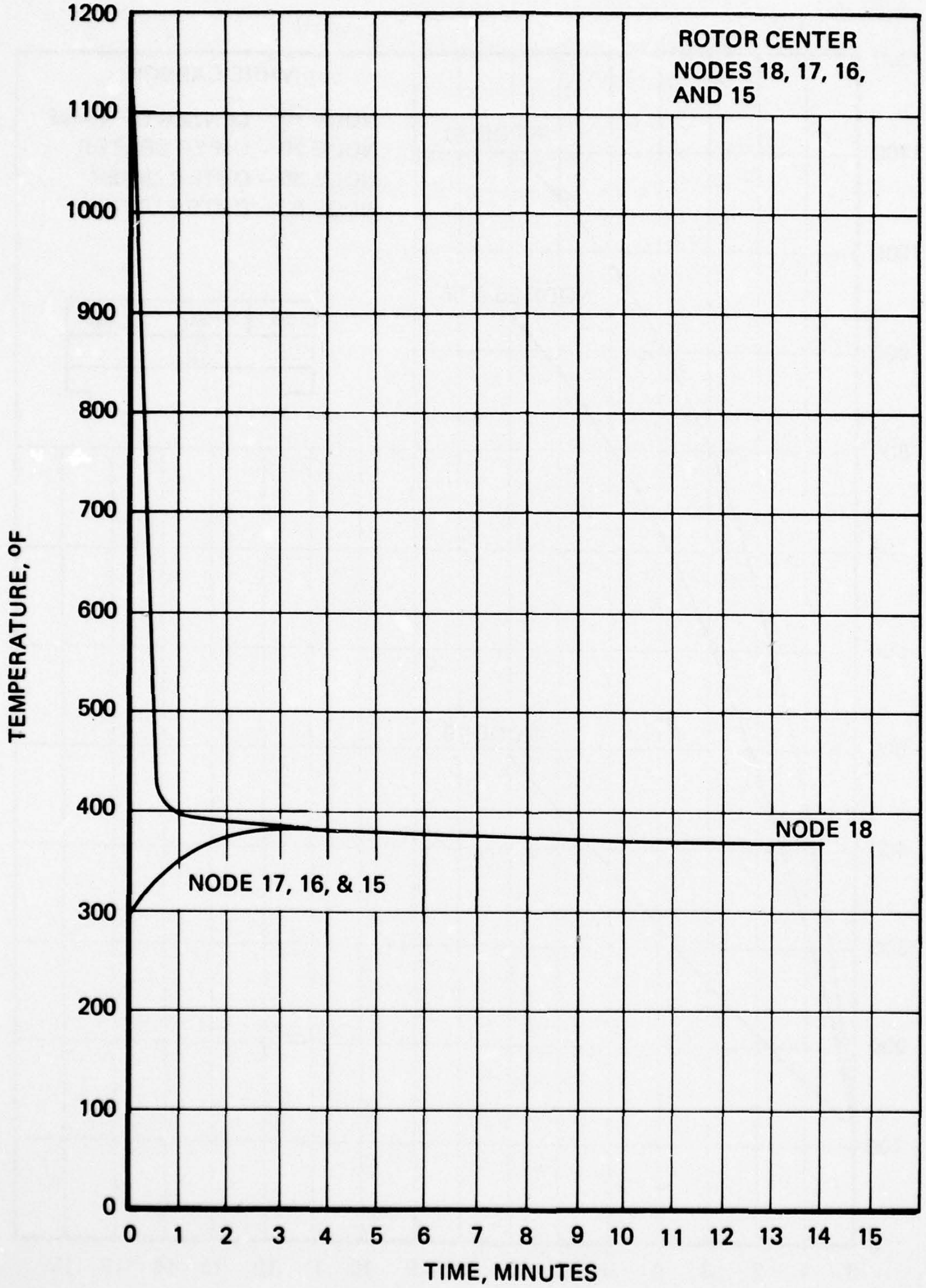


Figure 60. Fifteen-Minute Soakback at +120°F

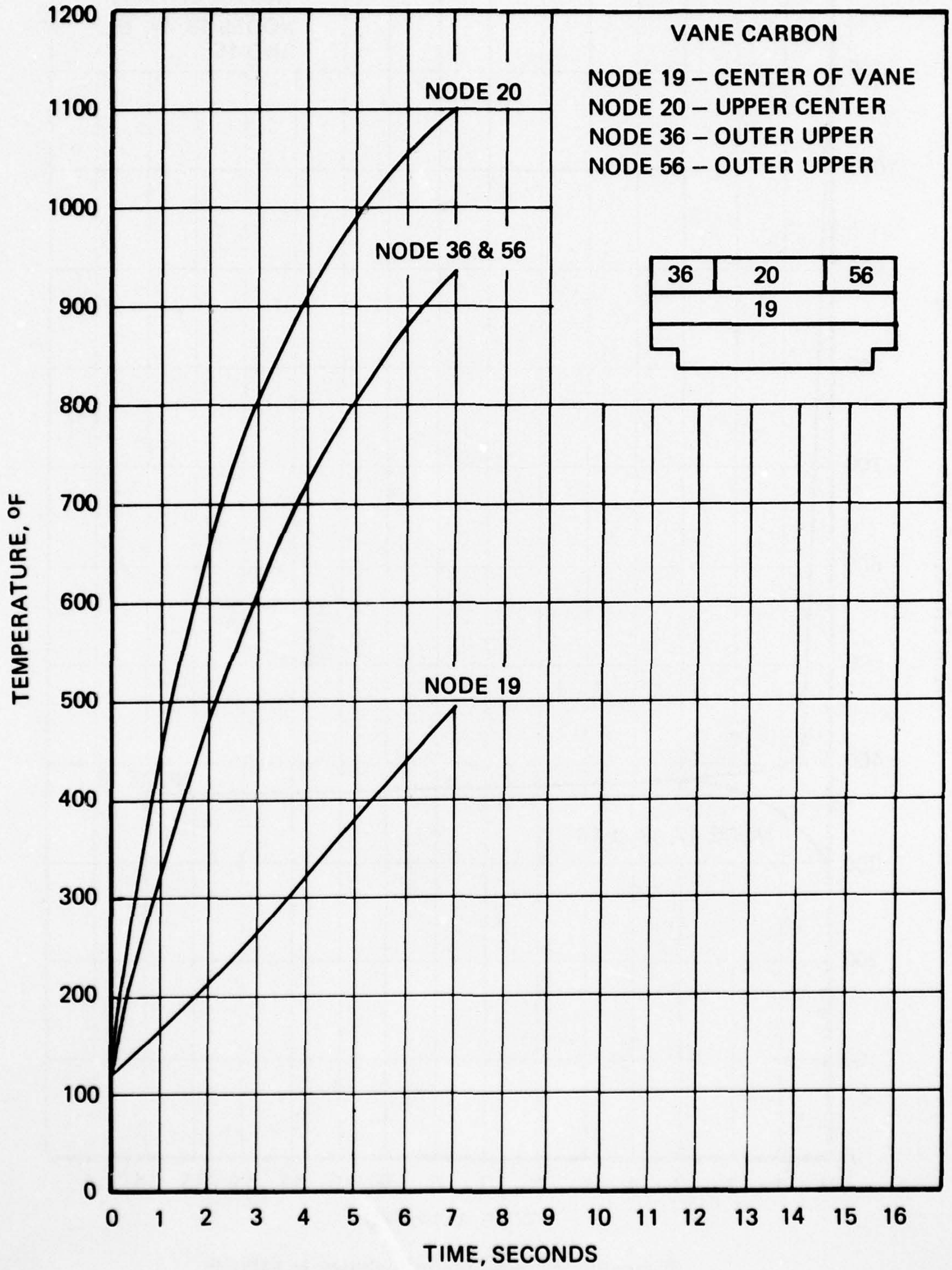


Figure 61. First 7-Second Firing at +120°F

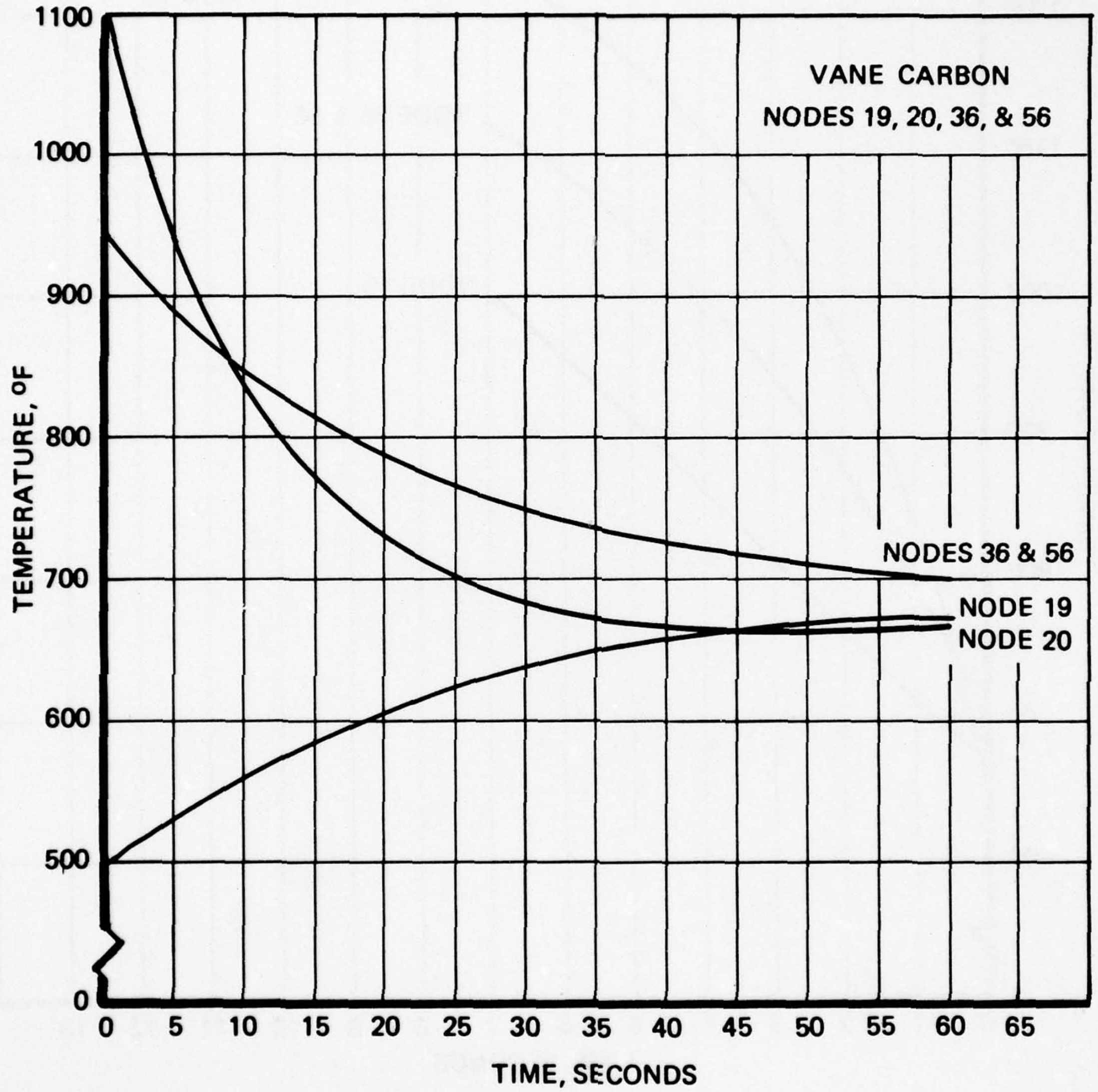


Figure 62. One-Minute Soakback at +120°F

24002-87

AD-A053 764 ROCKET RESEARCH CORP REDMOND WASH F/G 21/5
HYDRAZINE APU STARTER DESIGN.(U)
DEC 77 L D GALBRAITH F33615-76-C-2148
UNCLASSIFIED AFAPL-TR-77-76 NL

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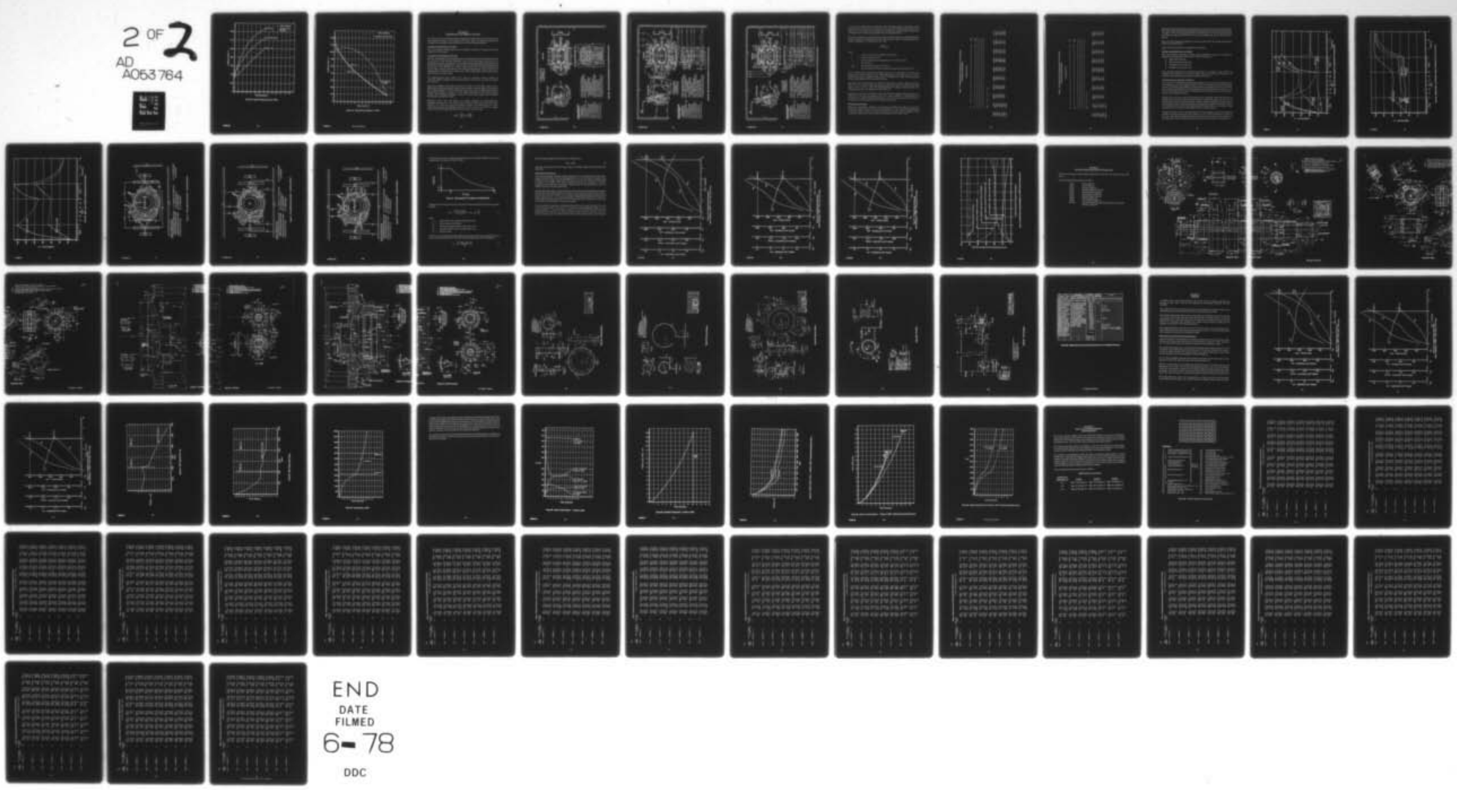
A053764



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6-78
DDC

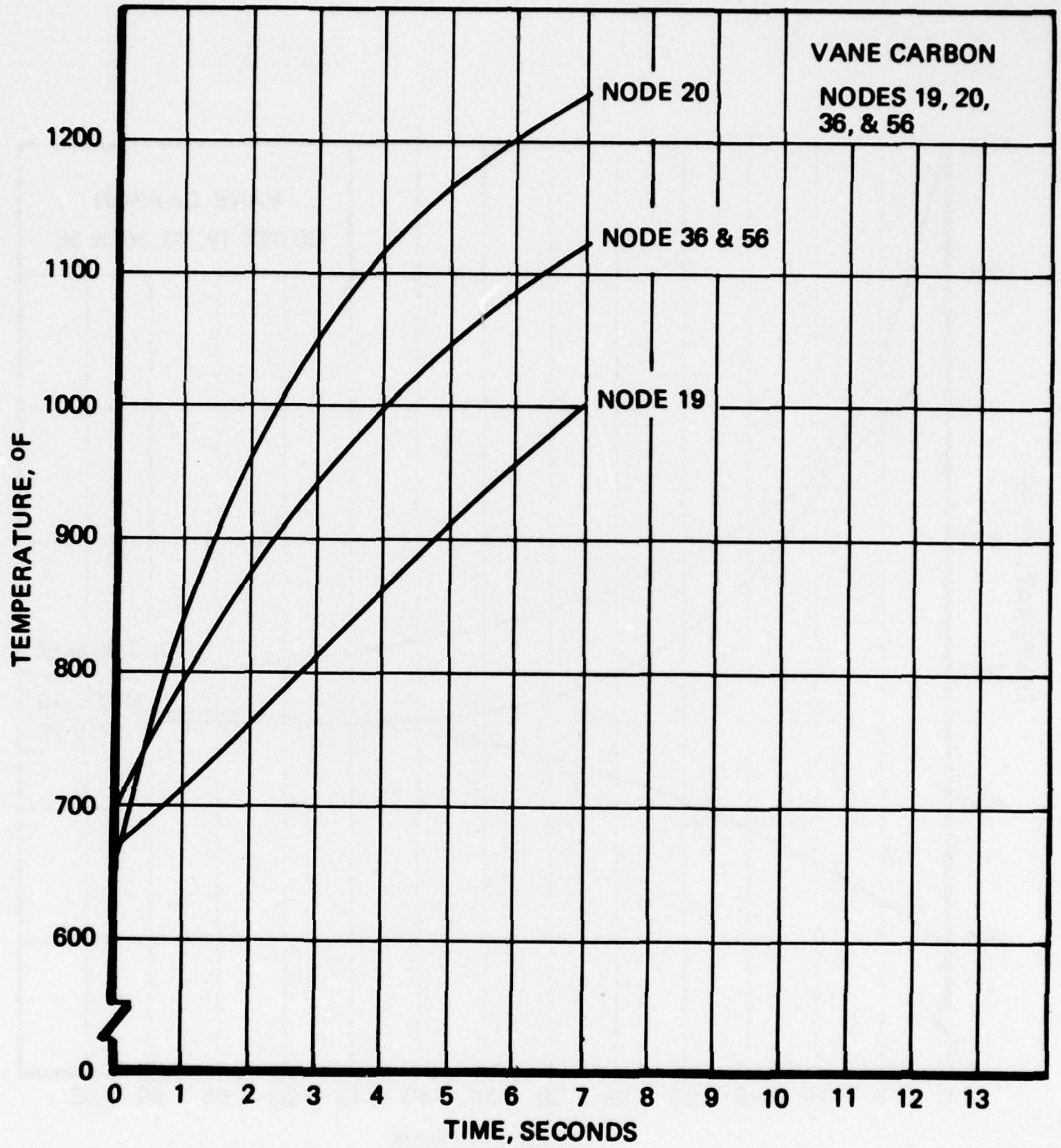


Figure 63. Second 7-Second Firing at +120°F

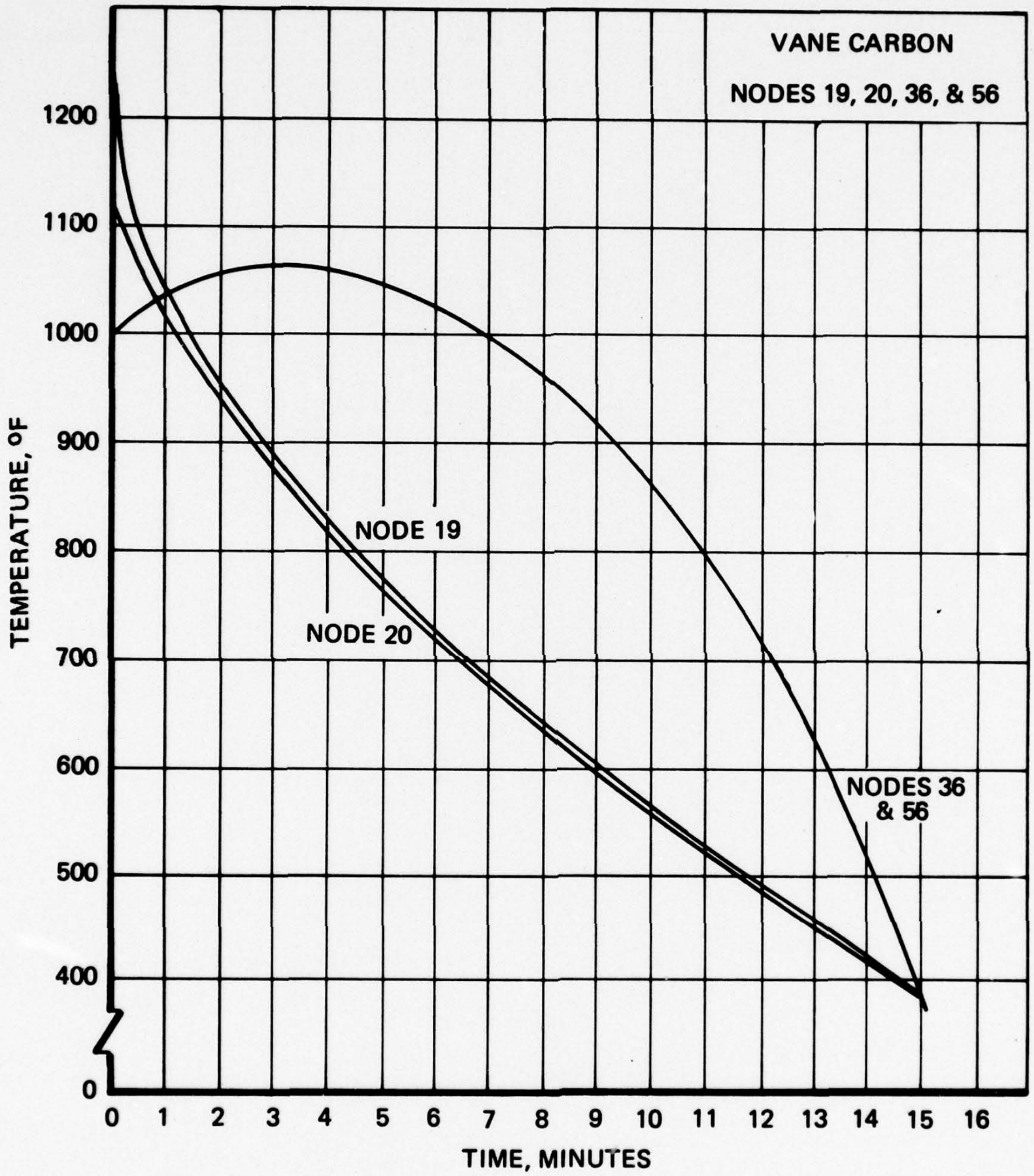


Figure 64. Fifteen-Minute Soakback at +120°F

SECTION III
PERFORMANCE AND THERMAL ANALYSES

This section discusses the methods developed and significant results attained from extensive thermal and performance analyses of the hydrazine APU starter motor. Two computer programs were developed. One is primarily thermal-structural and the other is thermal-performance.

THERMAL-STRUCTURAL ANALYSES

This section discusses thermal analysis work accomplished in support of verifying the structural integrity of the starter motor.

Thermal-Structural Modeling and Methods

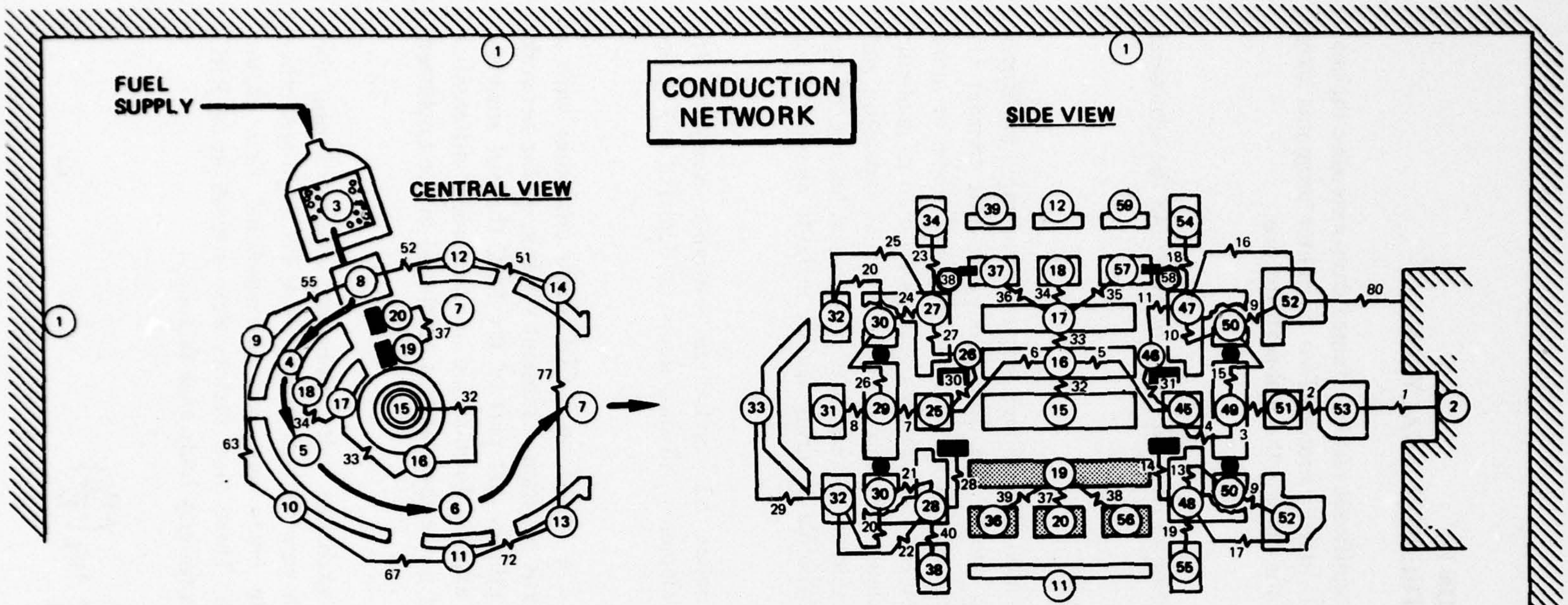
Networks corresponding to the thermal-structural model mentioned above are presented in Figures 65, 66, and 67. Each network corresponds to one of the three modes of heat transfer via conduction, convection, and radiation. It is necessary that the thermal-structural model be more detailed than the thermal-performance model in order to accurately predict local thermal gradients and hot spots. Such predictions are critical because they are used for thermal expansion and rotor-vane-stator tolerance determination. Such tolerance determination is critical because of the opposing goals of minimization of leakage losses while ensuring against metal-to-metal contact which could result in engine seizure.

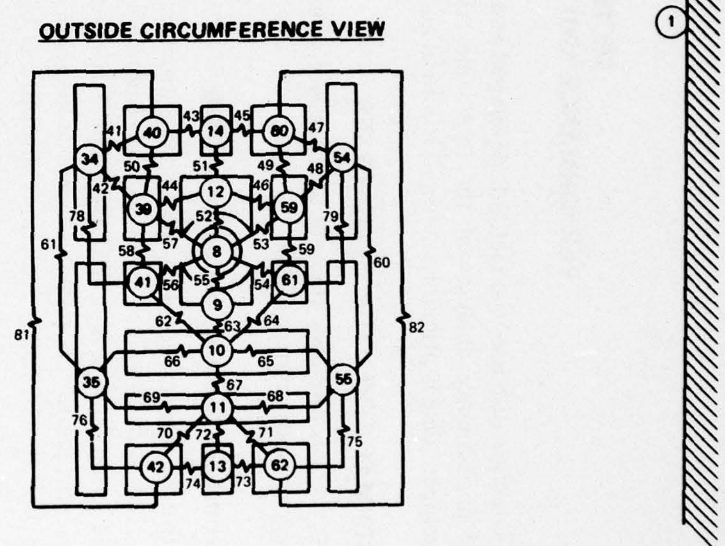
The thermal-structural model consists of 62 nodes, 82 conduction resistance elements, 86 convection resistance elements, and 60 radiation elements. All such items are depicted in Figures 65, 66, and 67.

Nodal finite difference heat balance equations are solved on a CDC 6600 computer with a RRC-developed, 500-node capacity, thermal analysis program. Transient solution of the network heat balance equations for the shadow analyses utilizes that part of the RRC thermal analyzer program which employs a precise exponential explicit formulation of the nodal differential equations. The mathematical technique employed is the same as that employed in the Lockheed thermal analyzer, an industry standard.

Multisurface, diffuse, grey body radiant heat exchange calculations are made utilizing the Oppenheim network method, in conjunction with view factors from NACA TN 2836 and other references. The motor was split into separate enclosures, and corresponding view factor conservation equations were established for each. These view factors were utilized in an RRC program which solves the following matrix equation for grey body view factors:

$$A_i \mathcal{F}_{ij} = \frac{A_i A_j}{\rho_i \rho_j} \epsilon_i \epsilon_j \left(\frac{-D_{ij}}{D} \right)$$





NODAL DESCRIPTIONS
(CENTRAL NODES)

1. SURROUNDINGS B.C.
2. MOTOR MOUNT B.C.
3. HOT GAS IN REACTOR

4, 5, & 6. EXPANDING HOT GASES
7. EXIT HOT GAS
8. REACTOR NOZZLE BOSS

9.–12. CTR MOTOR CASE
13. & 14. CTR EXH NOZZLE
15. & 16. CTR ROTOR SHAFT
17. & 18. CTR ROTOR PIE SECTS
19. & 20. CTR ROTOR VANES
21.–24. UNUSED NODES

(END SECTION NODES)

25. & 45. ROTOR SHAFT SECTS
26. & 46. ROTARY SEALS FOR SHAFT
27. & 47. UPPER END FLANGE CTR SECTS
28. & 48. LOWER END FLANGE CTR SECTS
29. & 49. SLEEVE, SHAFT & INNER RACE OF BEARINGS
30. & 50. OUTER RACE OF BEARINGS
31. THRUST WASHER, LOCKING NUT AND SHAFT SECTIONS
32. & 33. BEARING RETAINING CAP
34. & 54. UPPER END FLANGE OTR SECTS
35. & 55. LOWER END FLANGE OTR SECTS
36. & 56. OUTER ROTOR VANES
37. & 57. OTR ROTOR PIE SECTS
38. & 58. OTR ROTOR END SEALS
39. & 59., 40. & 60., 41. & 61., 42. & 62. ARE ALL SYMMETRIC MOTOR CASE REGIONS

Figure 65. Starter Motor Nodal Breakdown for Thermal/Structural Analysis

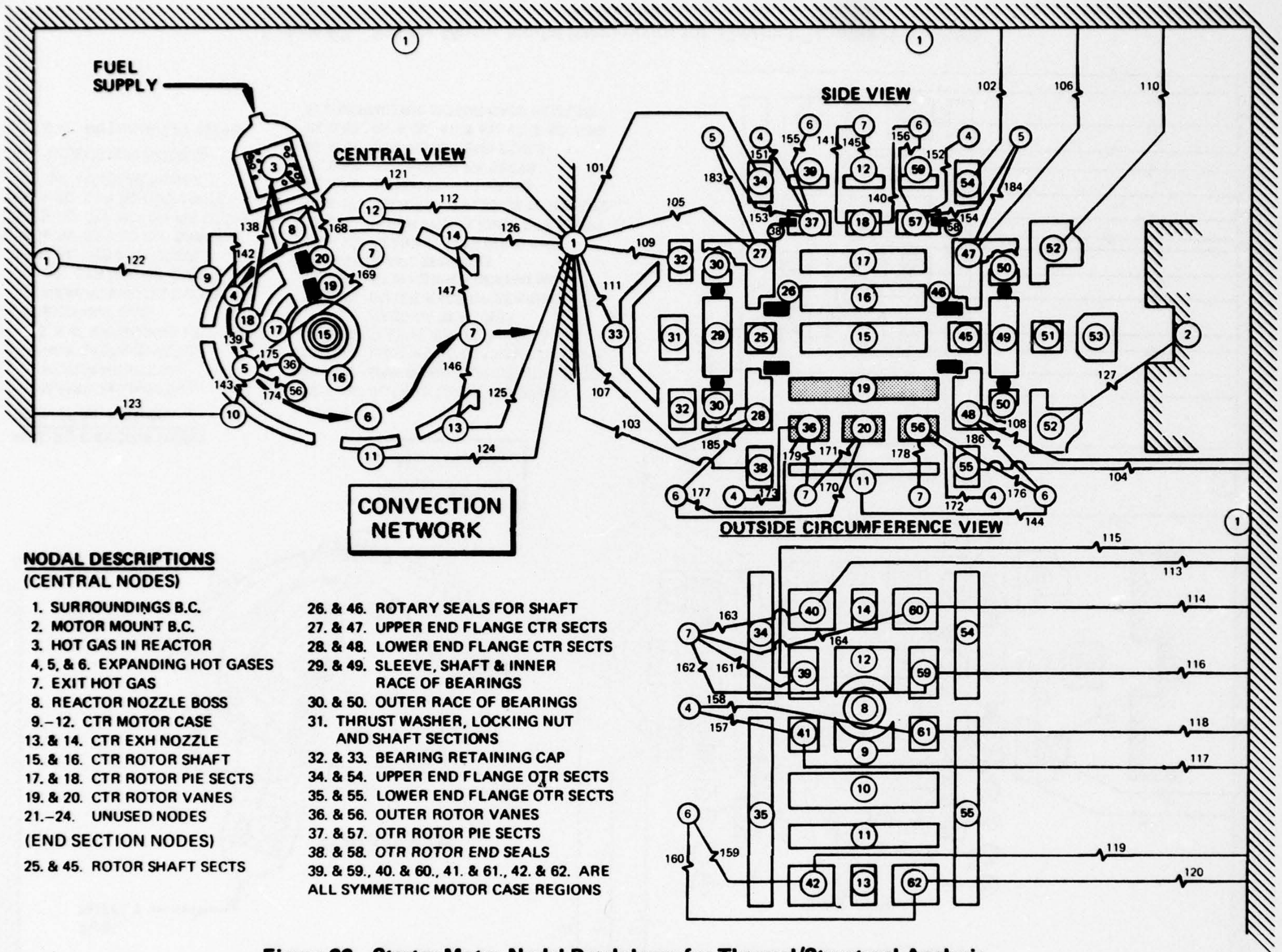


Figure 66. Starter Motor Nodal Breakdown for Thermal/Structural Analysis

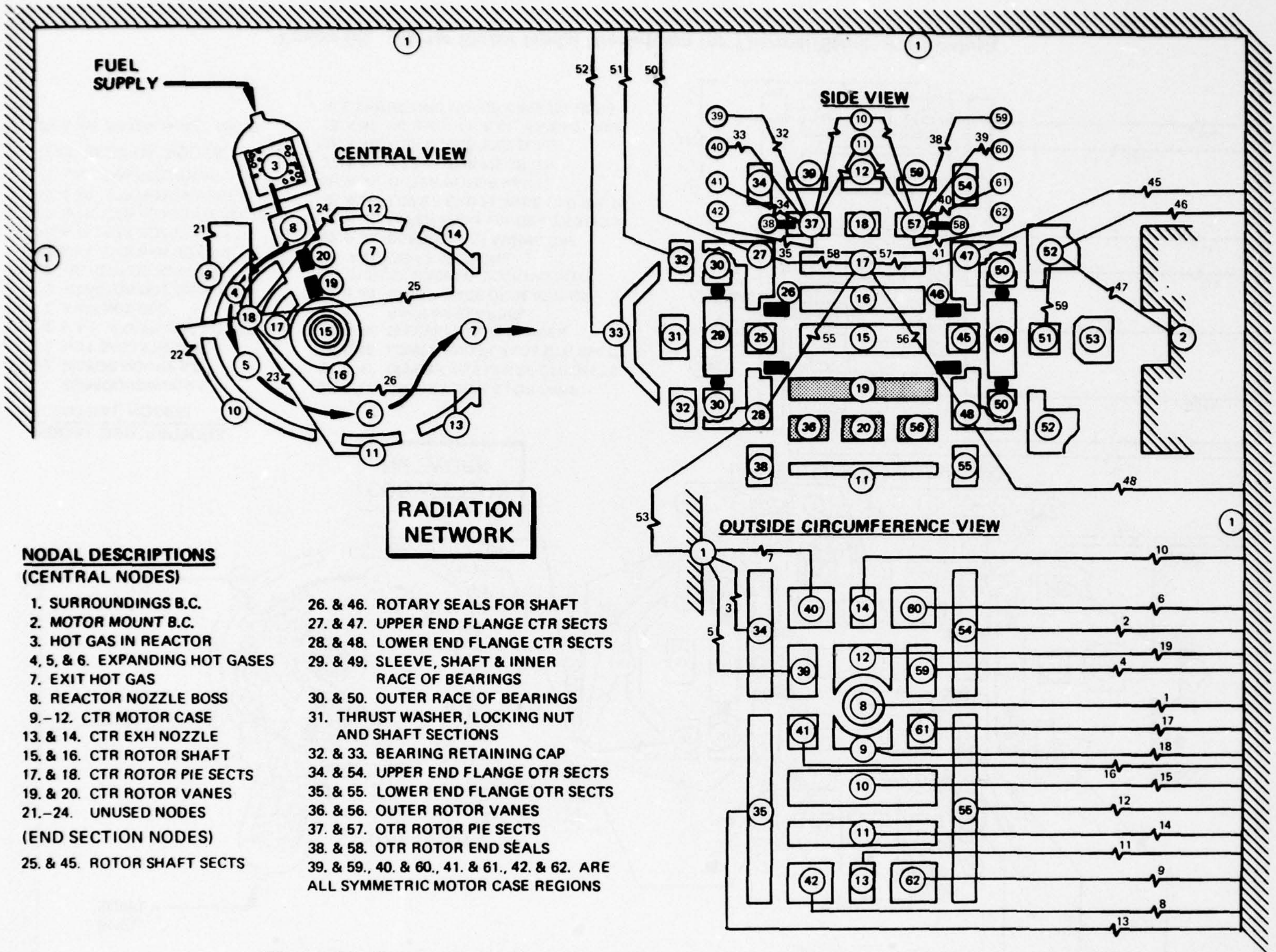


Figure 67. Starter Motor Nodal Breakdown for Thermal/Structural Analysis

in which D is the determinant of the coefficient matrix of radiation balances on all surfaces, and D_{ij} is the cofactor of its i-th row and j-th column. A's, ϵ's, and ρ's are respective areas, emittances, and reflectances of the surfaces in the enclosure. For most surfaces, a nominal emittance value of 0.5 was assumed which accounts for a reasonable degree of surface degradation.

For convection between the expanding hot gas and the rotor/stator surfaces, the following empirical formula was utilized as suggested in reference "Heat Transfer in Rotary Combustion Engines, by Atesmen, ASME Paper No. 75-HT-FF, June 18, 1974."

$$h = \frac{ak}{r} Rey_r^{\,b}$$

where:

h	=	convective heat transfer coefficient (Btu/hr-^{o}F-ft^2)
a	=	empirical constant (= 0.25)
k	=	thermal conductivity of expanding hot gas ($\approx$ 0.15 Btu/ft-hr-^{o}F)
r	=	rotor radius (ft)
Rey_r	=	Reynolds number based on rotor radius
b	=	constant derived from slope of Nusselt versus Reynolds number data (= 0.7)

Since all required motor operations are transient in nature, an average value of h in the above equation was assumed between 0 and 6,000 RPM. Values of h ranged from 211 to 709 Btu/ft^2-hr-^{o}F; however, stagnation values as high as 1,239 Btu/ft^2-hr-^{o}F were used where incoming hot gas initially impinges on the rotor and vane surfaces.

Much higher values than the above are reported by Wolgemuth in reference "Report on Task II, March 13, 1977"; however, RRC found that using such values resulted in unrealistic heat losses from the hot gas to the motor. The thermal-performance computer program results, to be subsequently discussed, also validated the above values of h.

Externally, the motor was assumed to be exposed to ambient air ranging in temperature from -65 to 120^{o}F. Free convection was assumed, and a heat transfer coefficient of approximately 1.0 Btu/hr-^{o}F-ft^2 was utilized. Radiation cooling was also utilized. Conduction cooling of the motor by the relatively massive gearbox and APU was assumed to be minimal.

Thermal-Structural Results

Based upon performance calculations and anticipated operational procedures, cold and hot environment thermal analyses were made assuming respective 12- and 7-second firings, followed by a 1-minute soakback, which was subsequently followed by another firing and soakback period. Temperature distributions at the end of the second firing are given in Tables 7 and 8.

Table 7. Local Starter Motor Temperatures at End of Second Firing for Hot Environment

(Temperatures °F)

$T_1 \longrightarrow T_{10}$

$T_{11} \longrightarrow T_{20}$

$T_{61} \longrightarrow$

120.0	120.0	1600.0	1450.0	1350.0	1200.0	1000.0	1494.9	1372.6	974.7
779.8	1004.2	757.4	760.7	265.7	288.8	292.9	1150.1	1005.6	1235.7
120.0	120.0	120.0	120.0	140.5	233.0	290.7	227.6	131.7	167.1
122.7	163.6	133.0	280.7	221.9	1120.9	1009.3	1007.2	837.5	601.4
1132.3	657.5	120.0	120.0	135.2	231.2	285.7	227.5	122.1	159.5
120.6	139.3	120.2	274.8	231.3	1120.9	1009.1	1007.0	787.1	599.4
1114.5	658.4								

Table 8. Local Starter Motor Temperatures at End of Second Firing for Cold Environment

(Temperatures ^{o}F)

$T_1 \longrightarrow T_{10}$

$T_{11} \longrightarrow T_{20}$

$T_{61} \longrightarrow$

-65.0	-65.0	1600.0	1450.0	1350.0	1200.0	1000.0	1546.0	1465.2	1188.4
973.2	1078.7	875.9	876.7	183.6	215.2	220.3	1181.3	1343.2	1337.9
-65.0	-65.0	-65.0	-65.0	-30.0	158.6	244.7	139.3	-42.4	30.7
-59.7	23.2	-39.3	232.1	133.7	1246.0	1119.2	1118.9	957.3	729.5
1322.6	810.2	-65.0	-65.0	-39.7	155.3	235.9	139.1	-61.4	16.3
-64.2	-26.4	-64.7	223.3	150.2	1246.0	1119.0	1118.7	915.9	727.2
1301.4	811.6								

Significant local motor temperatures taken from the above analysis results are plotted in Figures 68, 69, and 70. Figures 68 shows that substantial thermal gradients exist in the rotor and vanes from root (nodes 17 and 19) to exposed ends (nodes 18 and 20). Node 17 is 0.70 inch radially inside the rotor from the surface node 18. Node 19 is 1.26 inches radially inside the vane from the surface node 20.

Figure 69 shows temperature gradients for structures situated near the bearings, plus gradients within the bearings themselves.

Figure 70 shows typical stator case temperatures and gradients.

THERMAL-PERFORMANCE ANALYSES

This section discusses performance analysis work accomplished in support of verifying such significant operational parameters for the -65 to 130°F environment as:

- Motor speed versus time
- Motor inlet pressure versus time
- Propellant flow rate versus time
- Propellant consumed versus time

Other significant parameters such as shaft power available out of gearbox, torque available and required, motor efficiencies and individual energy losses (heat, leakage, and friction) are all tabulated in the actual computer printouts, summarized in Section VI.

Thermal-Performance Modeling and Methods

As mentioned in "Thermal-Structural Modeling and Methods," it is not necessary to split the motor into as many nodes for the thermal-performance model as the thermal-structural model. However, the same mathematical finite difference transient solution techniques are used for both models. Thus, networks corresponding to the thermal-performance model are presented in Figures 71, 72, and 73, and consists of only 18 nodes, 19 conduction resistance elements, 21 convection resistance elements, and 22 radiation elements.

Actually, heat loss is only a part of the performance loss calculation. Other significant parts are leakage and vane friction. The primary reason for the work represented in Figures 71, 72, and 73 is the utilization of the general finite difference transient solution capabilities of the RRC thermal analyzer program. Since this general program has subprogramming capabilities, leakage loss, friction loss, integrated heat loss, and all other significant performance parameters can be computed during each iterative time step that the main program performs a nodal heat balance.

Leakage and friction losses were incorporated from the work previously performed by Wolgemuth, presented in reference "Report on Task II, March 13, 1977," which was performed in support of this effort. The minimum leakage design in the above reference was chosen for incorporation into the performance model, and significant design attention has been expended to achieve this goal.

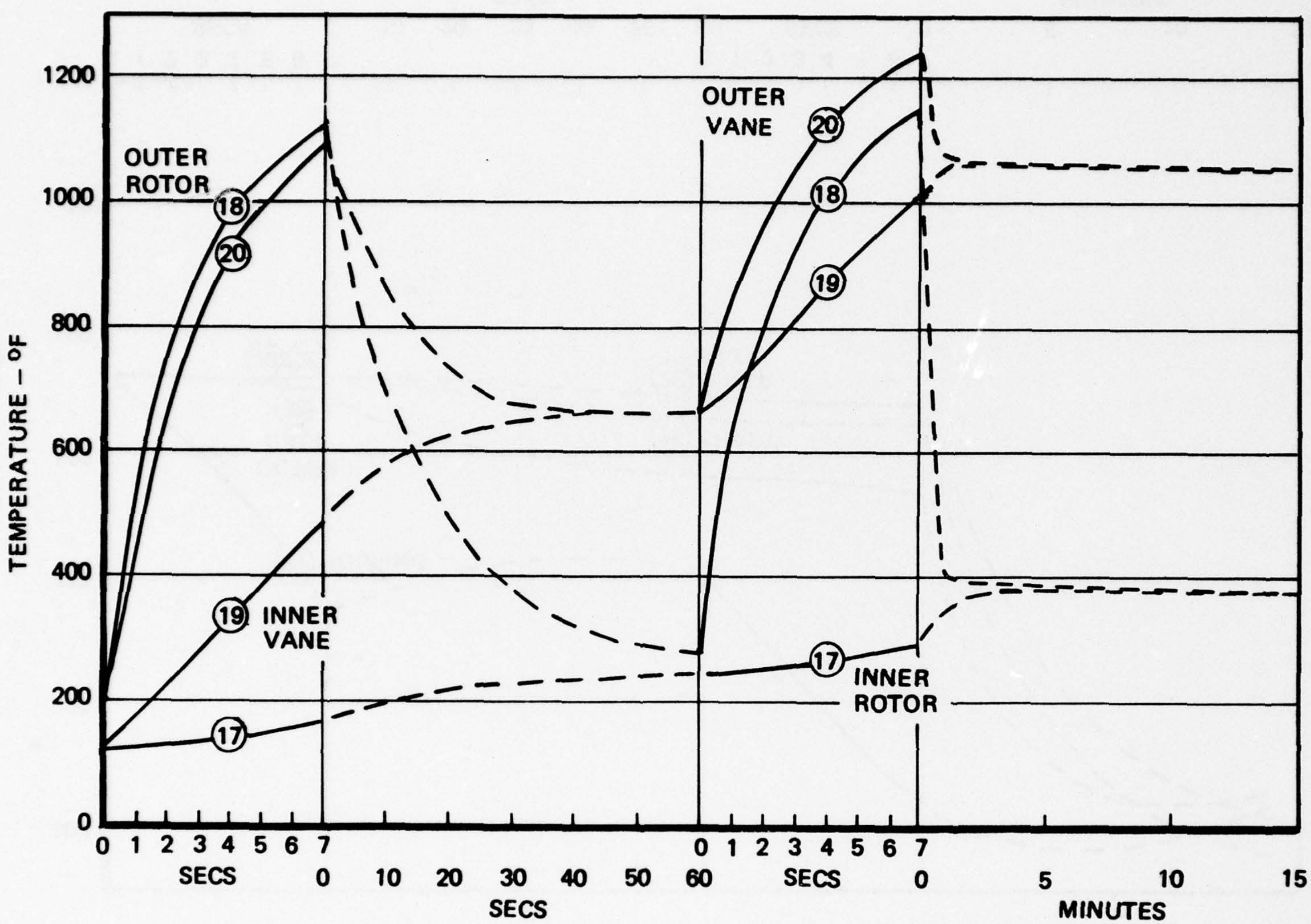


Figure 68. Rotor and Vane Transient Temperatures (Hot Environment)

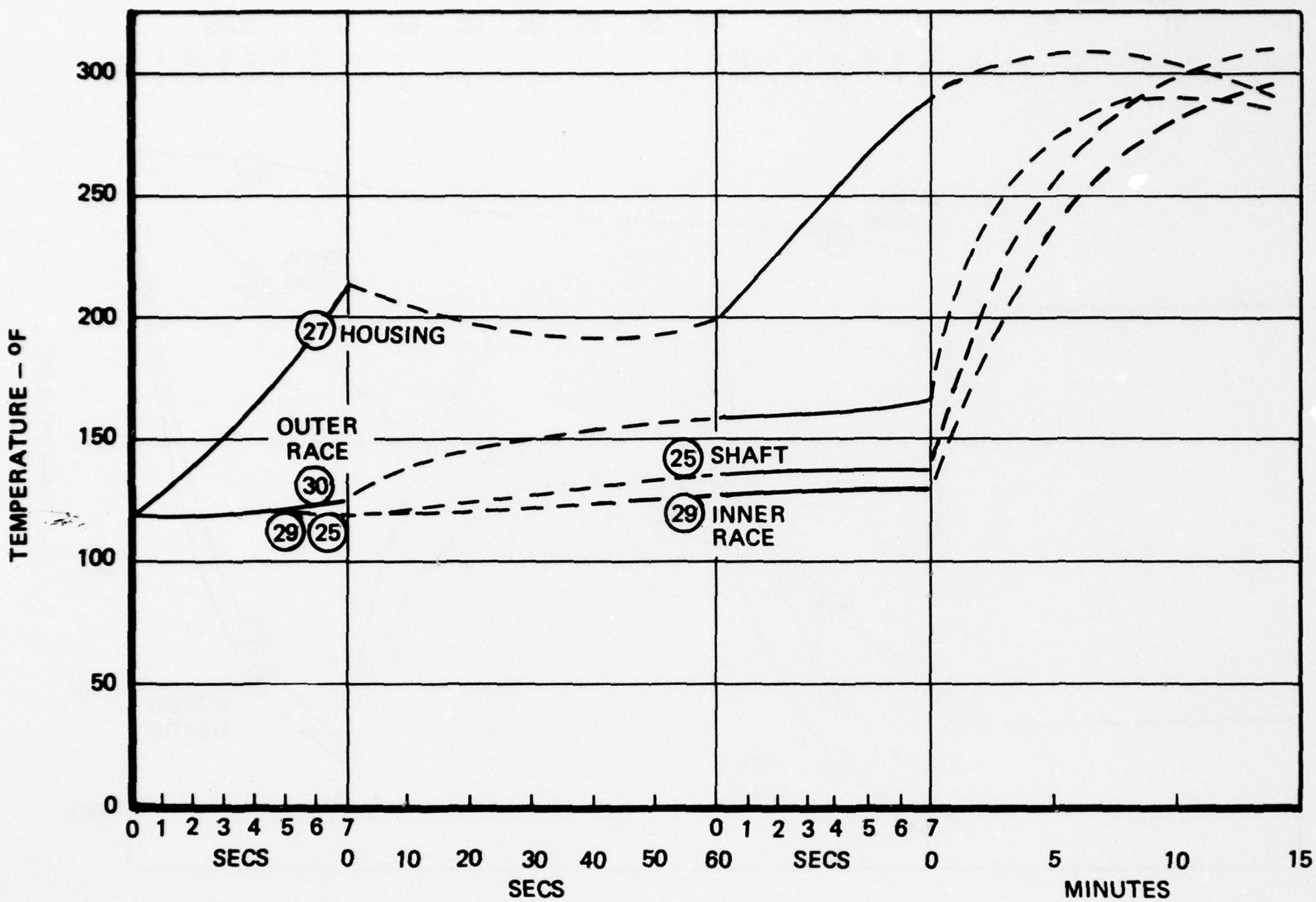


Figure 69. Bearing, Shaft, and Housing Transient Temperatures (Hot Environment)

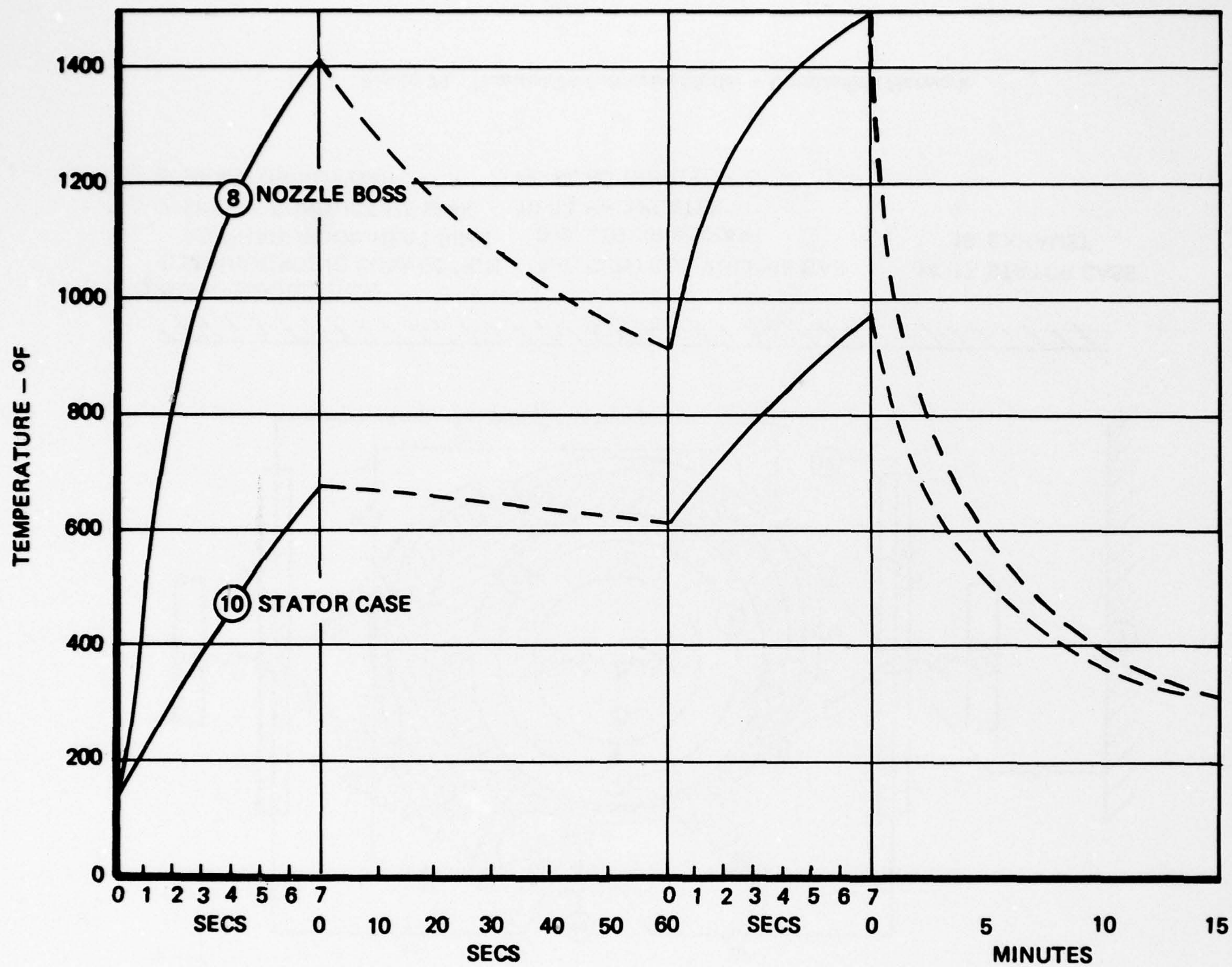
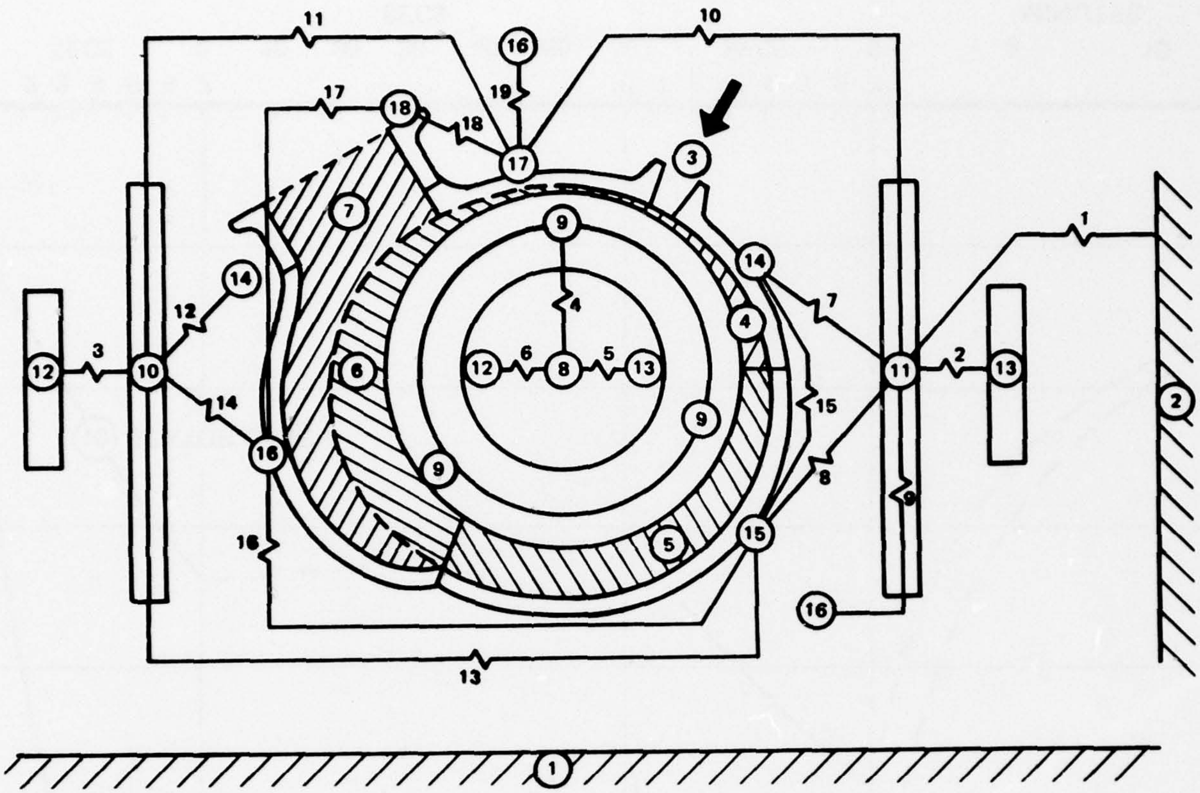


Figure 70. Stator Local Transient Temperatures (Hot Environment)



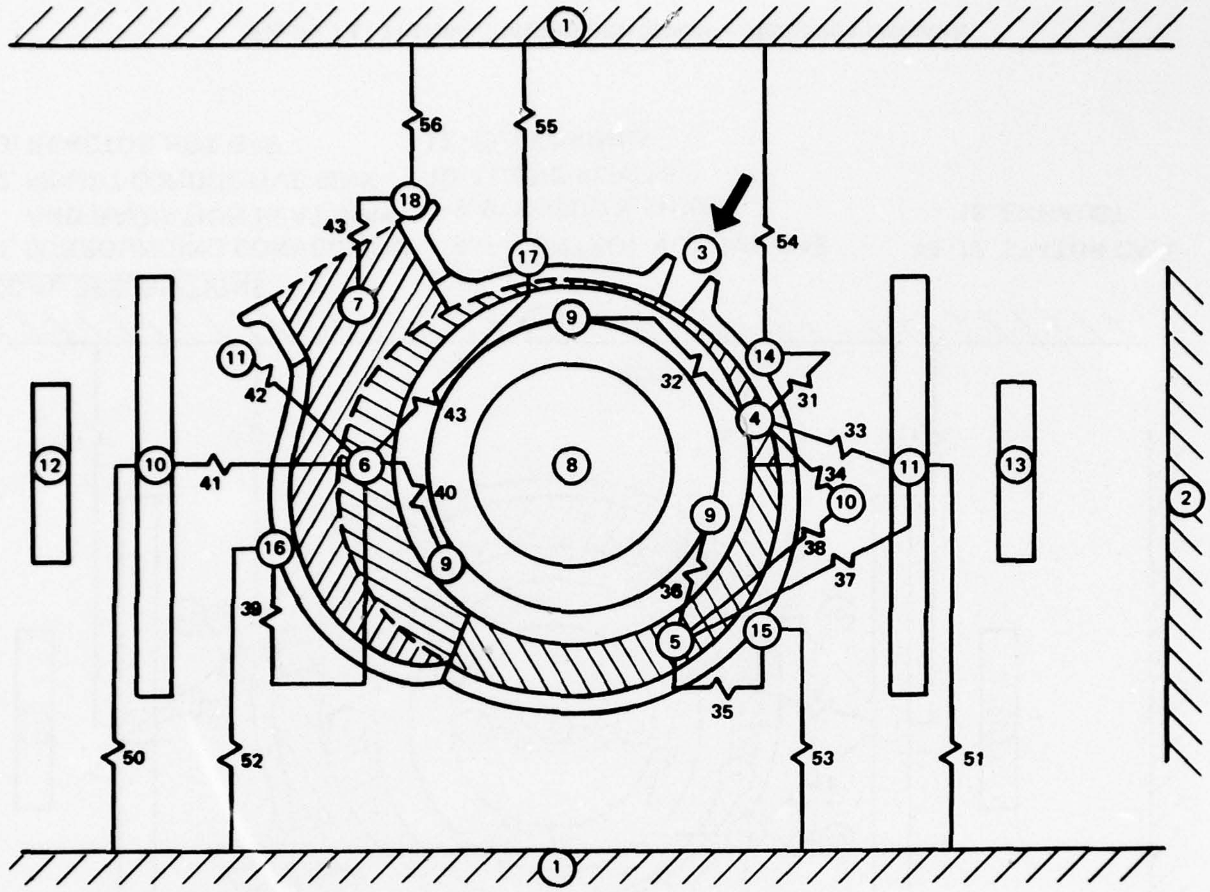
NODAL DESCRIPTIONS

1. SURROUNDING CONVECTION AND RADIATION HEAT SINK
2. MOUNT CONDUCTIVE SINK
3. REACTOR HOT GAS

4.-7. CONTROL VOLUME GAS
8.-9. ROTOR & SHAFT
10.-11. END PLATES
12.-13. BEARINGS

14.-17. STATOR CASE
18. EXHAUST

Figure 71. Thermal/Performance Model – Conduction Network



NODAL DESCRIPTIONS

1. SURROUNDING CONVECTION AND RADIATION HEAT SINK
2. MOUNT CONDUCTIVE SINK
3. REACTOR HOT GAS

4.-7. CONTROL VOLUME GAS
8.-9. ROTOR & SHAFT
10.-11. END PLATES
12.-13. BEARINGS

14.-17. STATOR CASE
18. EXHAUST

Figure 72. Thermal/Performance Model – Convection Network

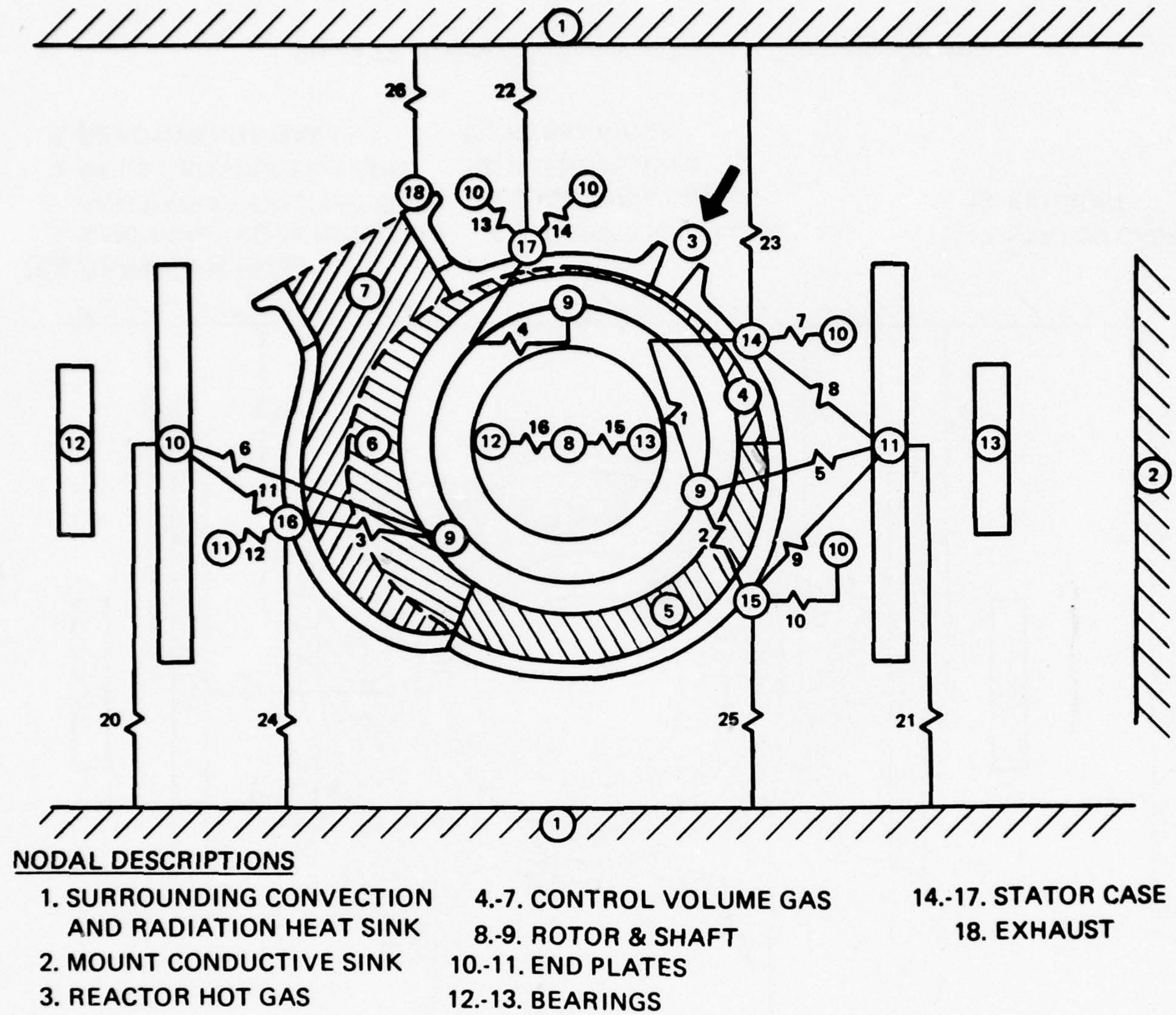


Figure 73. Thermal/Performance Model — Radiation Network

The performance model is essentially developed around the ideal energy available from the general expander open cycle depicted in Figure 74 below.

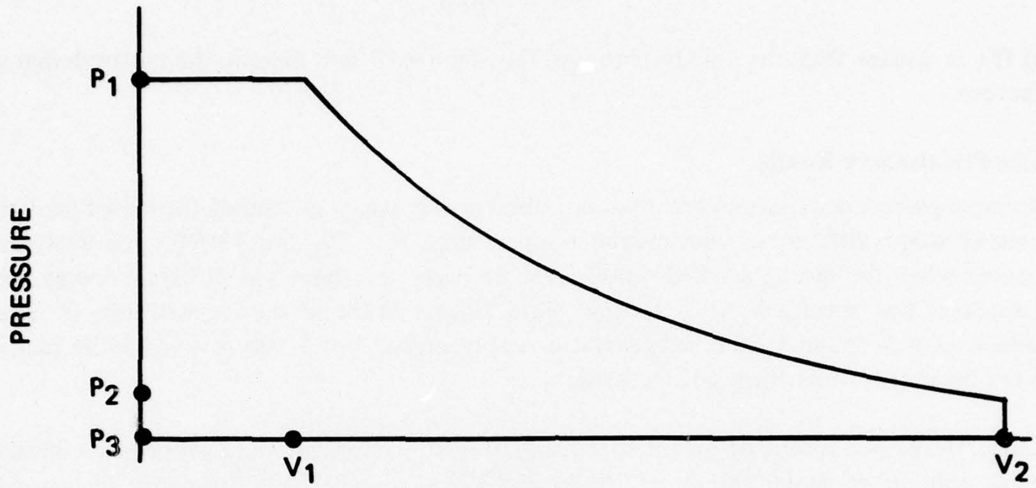


Figure 74. Thermodynamic P-V Diagram for Expander Motor

Summing the PV work around the above cycle gives the following relation for ideal energy available, Q_I in Btu.

$$Q_I = \frac{\gamma(P_1V_1 - P_2V_2)}{(\gamma - 1)J} + (P_2 - P_3)\frac{V_2}{J} \tag{1}$$

where:

P_1	~	inlet pressure in first control volume between vanes
V_1	~	volume of first control volume
P_2	~	isentropic expansion pressure from P_1 and V_1 to V_2
V_2	~	maximum expanded volume in design relative to V_1
P_3	~	ambient pressure

To verify that the design will perform satisfactory heat Q_Q, friction Q_F, and leakage Q_L, losses must be subtracted from Q_I above. This results in the following equation for actual efficiency.

$$\eta_A = \frac{Q_I - (Q_Q + Q_F + Q_L)}{Q_I} \tag{2}$$

Then, the energy available for shaft work, Q_A, is calculated from

$$Q_A = \eta_A Q_I \tag{3}$$

and if Q_A is greater than the energy required, Q_R, by a sufficient margin, the motor design will be satisfactory.

Thermal-Performance Results

The thermal-performance computer program, discussed above, was utilized for motor performance analyses at three different environmental temperatures, -65, 59, and 130°F. The analyses were terminated when the motor reached 6,000 RPM. In each case there was sufficient energy available to overcome the specified APU torque requirements without the expenditure of excessive propellant. It was found that a gas generator supply pressure of 1,500 psia would be required in order for the motor to perform satisfactorily.

Typical performance results of motor speed, inlet pressure, flow rate and propellant consumption all versus time are presented in Figures 75, 76, and 77. As shown, the performance analysis predicts that the motor will start the APU in 6 to 10 seconds, which verifies the assumed thermal-structural analysis time periods of 7 to 12 seconds mentioned in "Thermal-Structural Results." Furthermore, fuel consumed per start ranges from 0.97 to 1.34 lbm. More fuel is expended for the cold starts because APU torque requirements are significantly higher.

All other performance parameters calculated simultaneously with the results in Figures 75, 76, and 77 are presented in Table 9 of Section VI. As a matter of interest, significant energy items contained in equations 1, 2, and 3 are plotted in Figure 78 for the -65°F start. These data were taken from Section VI. At the start, heat transfer and friction losses are small because the motor is not turning; but leakage losses are relatively higher because of cold clearances between all moving parts.

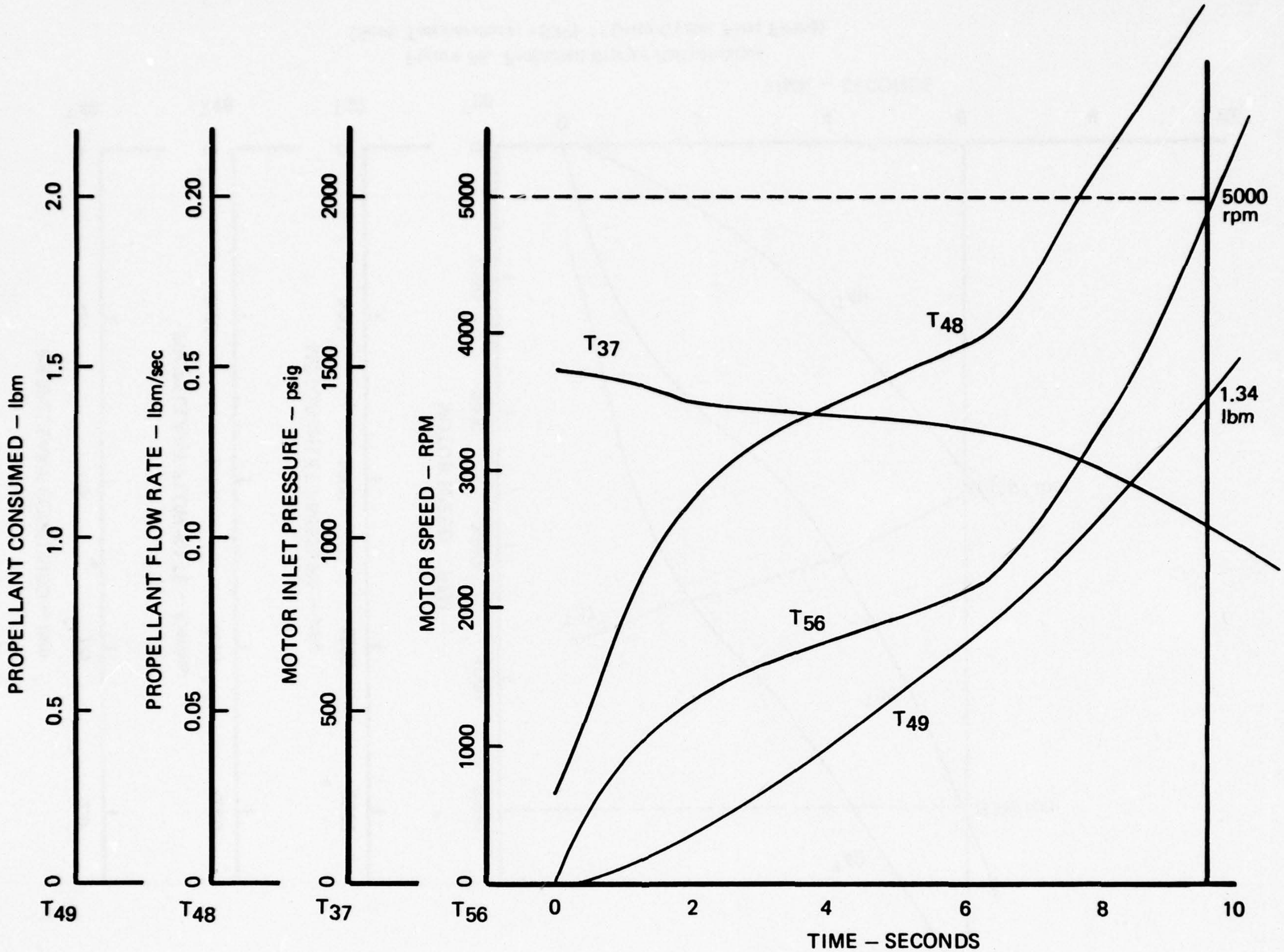


Figure 75. Projected Starter Performance
(Soak Temperature: -65°F ~ Duty Cycle: First Firing)

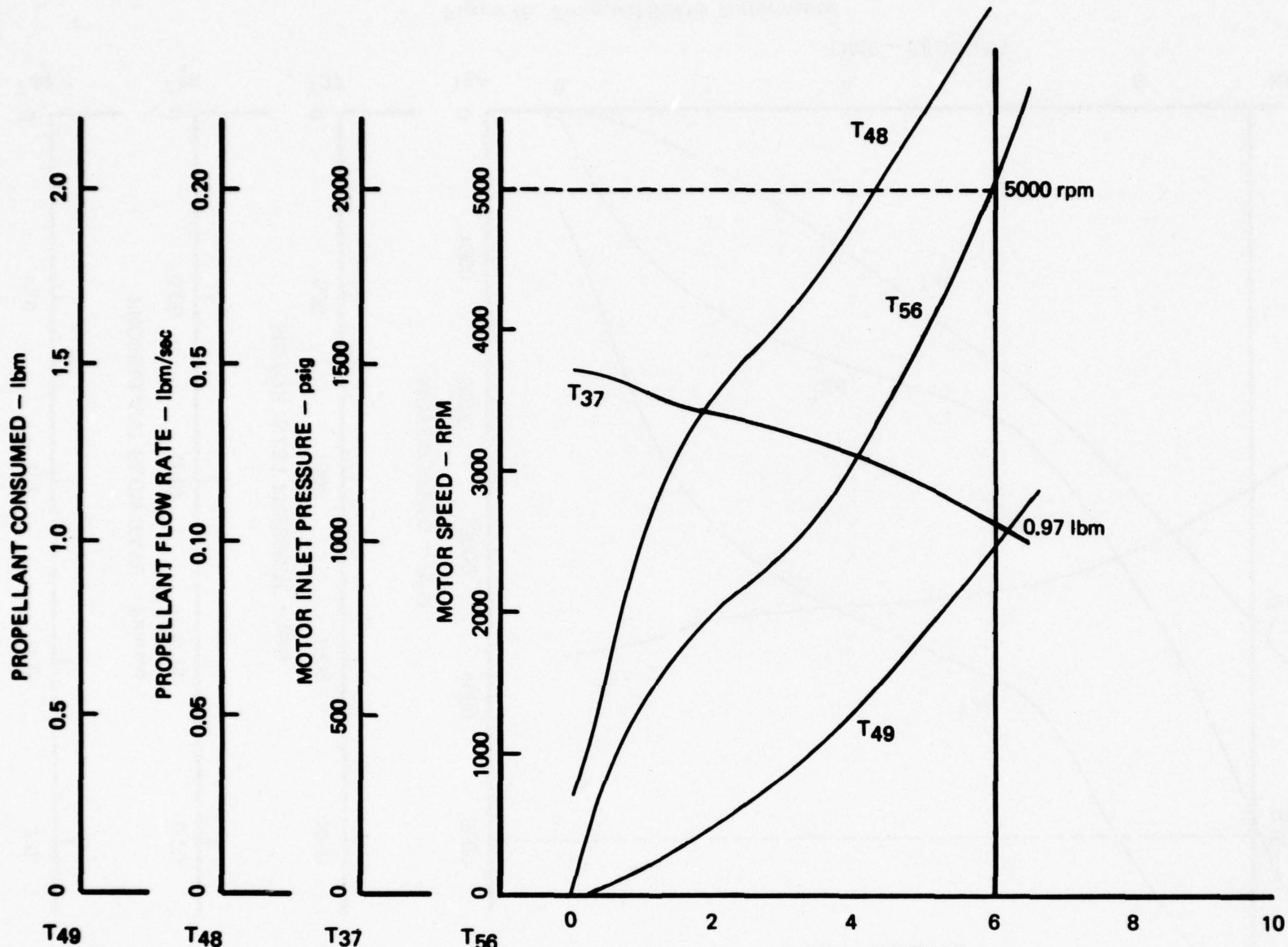


Figure 76. Projected Starter Performance
(Soak Temperature: +59°F ~ Duty Cycle: First Firing)

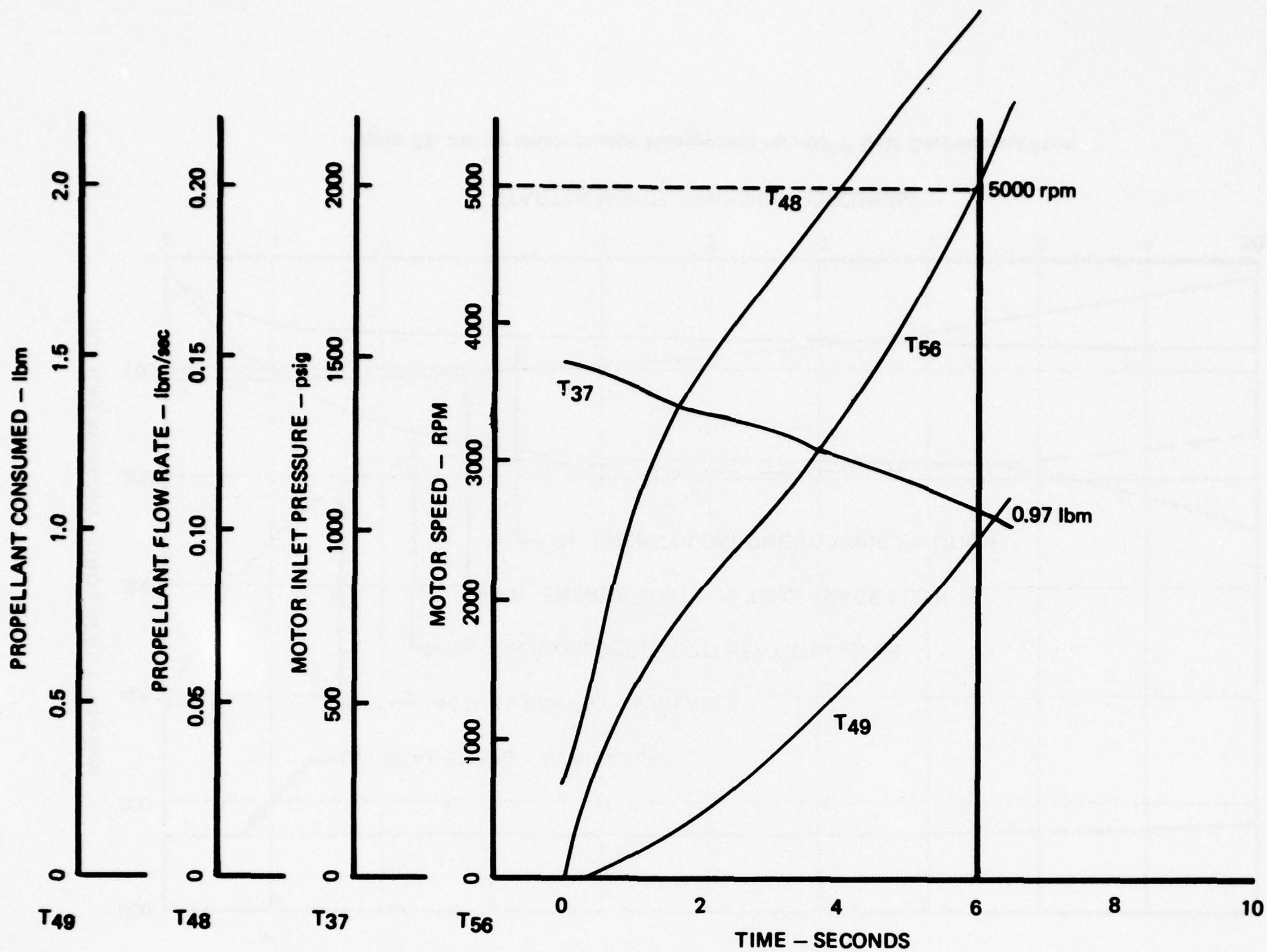


Figure 77. Projected Starter Performance
(Soak Temperature: +130°F ~ Duty Cycle: First Firing)

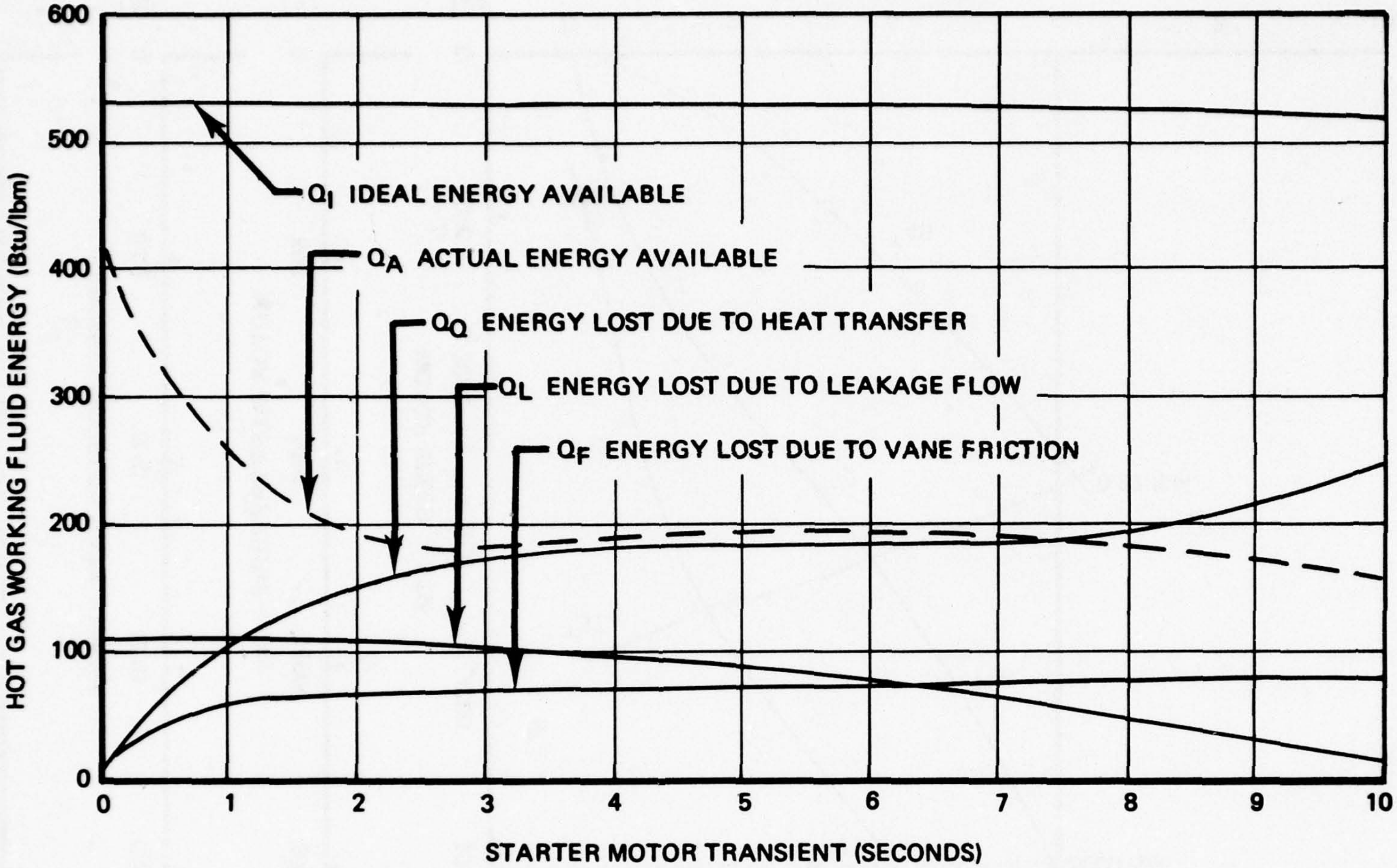


Figure 78. Starter Motor Energy Management for -65°F Cold Environment Start

SECTION IV
DETAILED DESIGN DRAWINGS AND PARTS LIST

This section presents the detailed design drawings and the parts list for the hydrazine-fueled APU starter.

The detailed RRC design drawings are as follows:

26651	–	Rotor, Figure 79
26652	–	Stator, Figure 80
26653	–	End Plate, Figure 81
26654	–	End Plate (Output), Figure 82
26656	–	Bearing Retainer, Figure 83
26657	–	Shim and Spring, Figure 84
26658	–	Bearing Retainer, Figure 85
26684	–	Rotor Seal, Figure 86
26685	–	Vane Assembly, Figure 87
SK 5957	–	Materials Summary Drawing (including parts list and weight summary), Figure 88

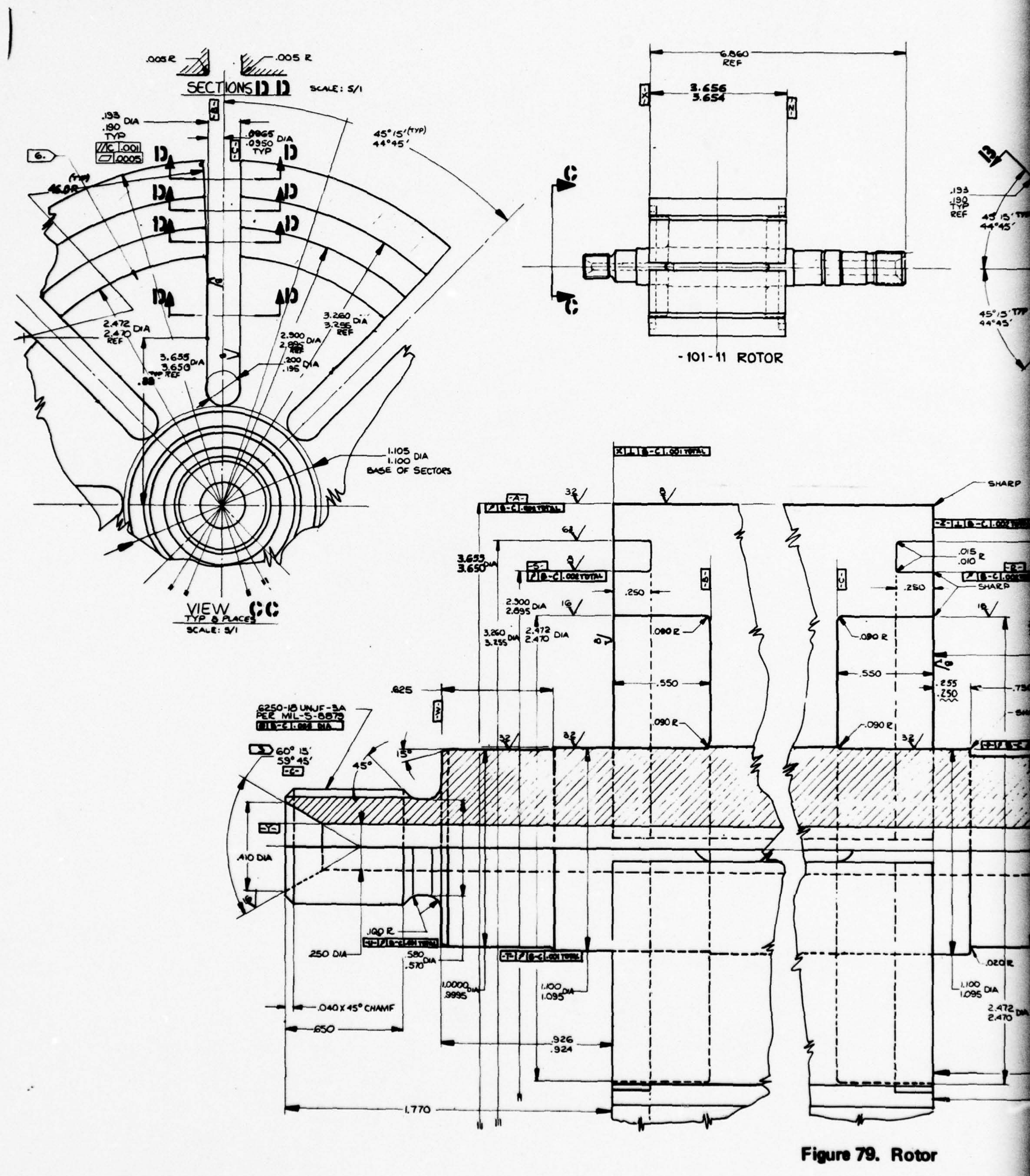
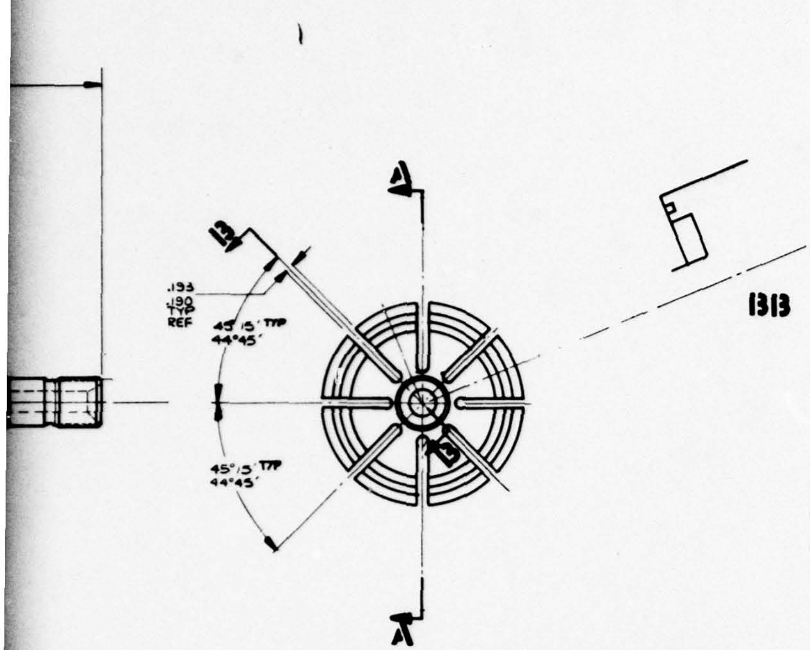
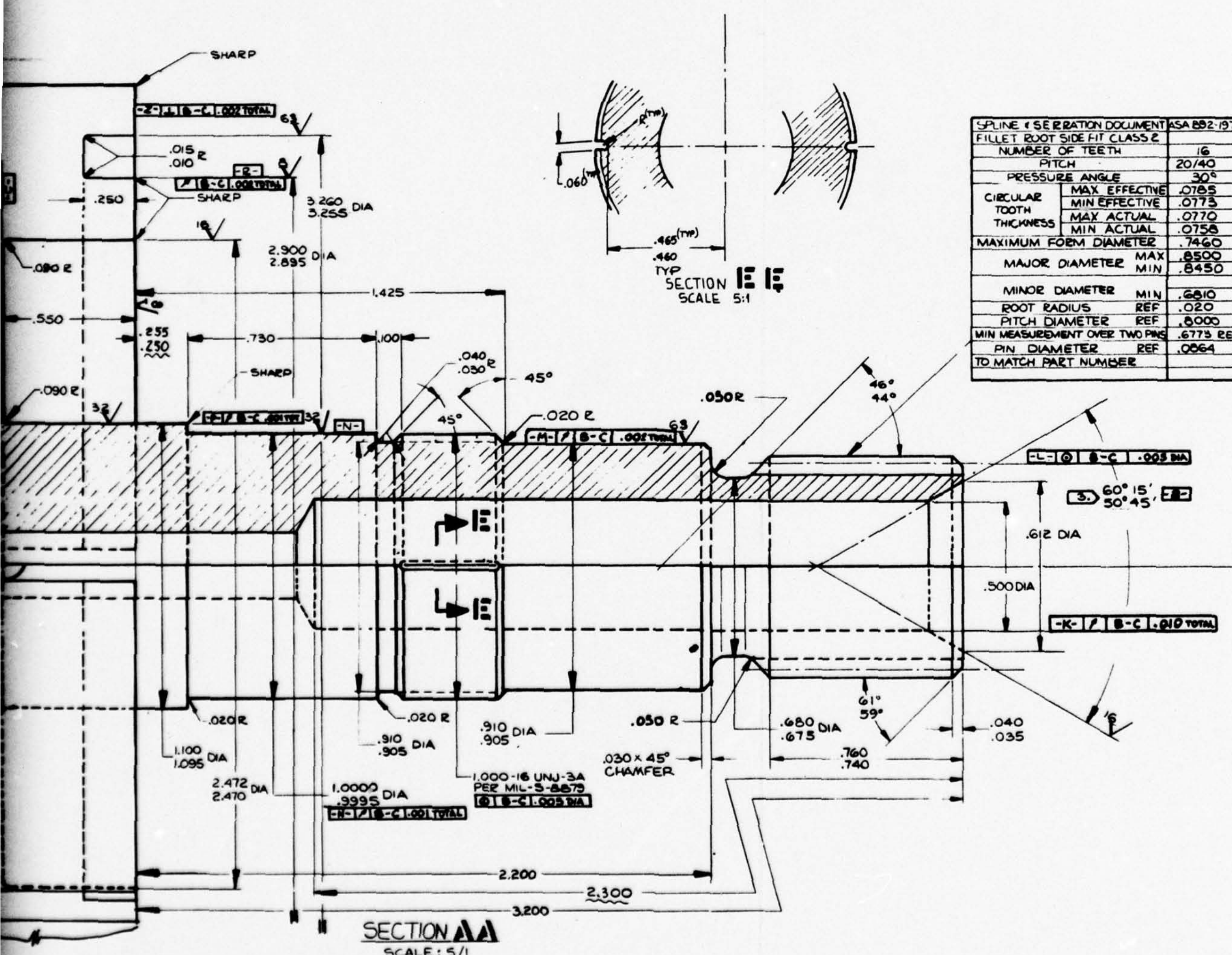


Figure 79. Rotor

2

1. INTERPRET DRWG PER MIL-STD-100B
2. 125/ FINISH ALL SURFACES EXCEPT AS NOTED
3. ROTOR SHAFT SHALL BE MACHINED USING GRINDING CENTERS.
4. PART SHALL BE DEGREASED BEFORE ASSEMBLY.
5. BREAK ALL SHARP EDGES .03-.06 EXCEPT AS NOTED.
6. IDENTIFY BY ELECTRO ETCHING IN AREA SHOWN.
7. PRODUCTION MATERIAL: HAYNES ALLOY R41 PER AMS 5713 PRECIPITATION H.T. PER AMS 5713. ULTRASONIC INSPECT PER RRC-PS-0044 CLASS A. PENETRANT INSPECT PER RRC-PS-0049.





SPLINE & SERRATION DOCUMENT		ASA B92.1-1970
FILLET ROOT SIDE FIT CLASS 2		
NUMBER OF TEETH		16
PITCH		20/40
PRESSURE ANGLE		30°
CIRCULAR TOOTH THICKNESS	MAX EFFECTIVE	.0785
	MIN EFFECTIVE	.0775
	MAX ACTUAL	.0770
	MIN ACTUAL	.0758
MAXIMUM FORM DIAMETER		.7460
MAJOR DIAMETER	MAX	.8500
	MIN	.8450
MINOR DIAMETER	MIN	.6810
ROOT RADIUS	REF	.020
PITCH DIAMETER	REF	.8000
MIN MEASUREMENT OVER TWO PINS		.6775 REF
PIN DIAMETER	REF	.0864
TO MATCH PART NUMBER		

re 79. Rotor

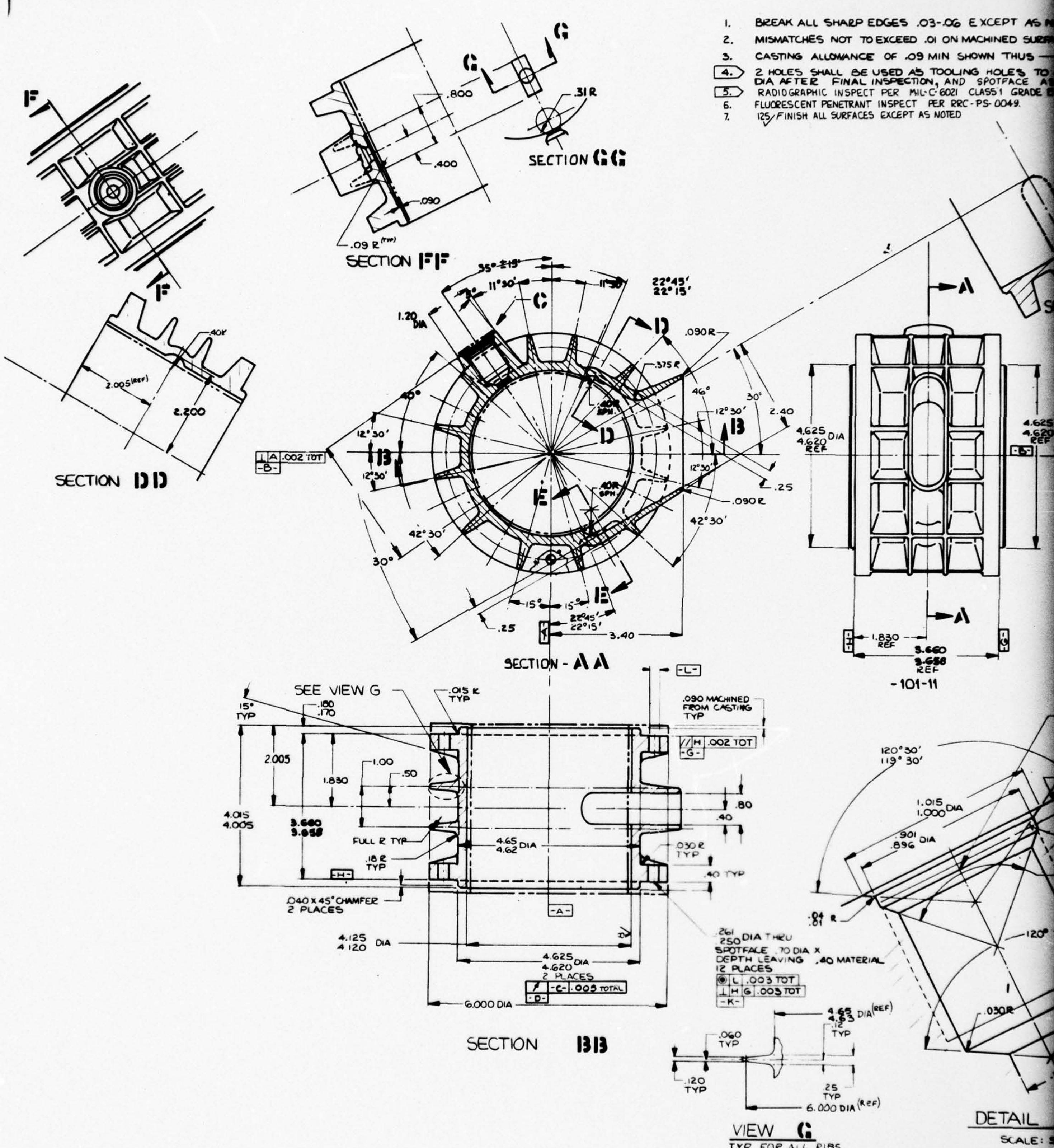


Figure 80. Stator

2

1. BREAK ALL SHARP EDGES .03-.06 EXCEPT AS NOTED.
2. MISMATCHES NOT TO EXCEED .01 ON MACHINED SURFACES AND SHALL BLEND SMOOTHLY.
3. CASTING ALLOWANCE OF .09 MIN SHOWN THUS
4. 2 HOLES SHALL BE USED AS TOOLING HOLES TO ESTABLISH -A-. OPEN HOLES TO .250-.261 DIA AFTER FINAL INSPECTION, AND SPOTFACE AS SHOWN.
5. RADIOGRAPHIC INSPECT PER MIL-C-6021 CLASS 1 GRADE B (PRODUCTION PARTS ONLY)
6. FLUORESCENT PENETRANT INSPECT PER RRC-PS-0049.
7. 125 FINISH ALL SURFACES EXCEPT AS NOTED

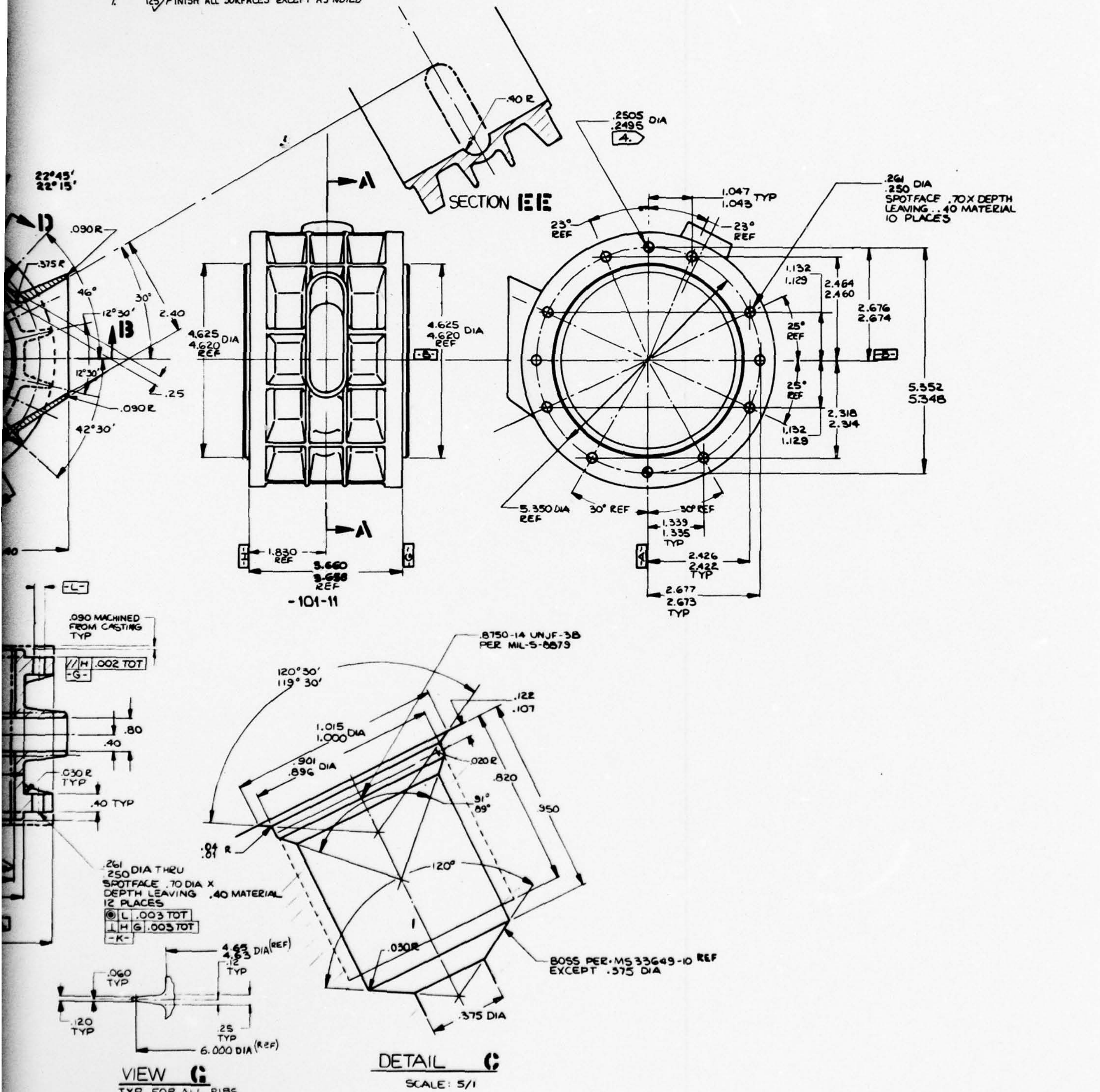


Figure 80. Stator

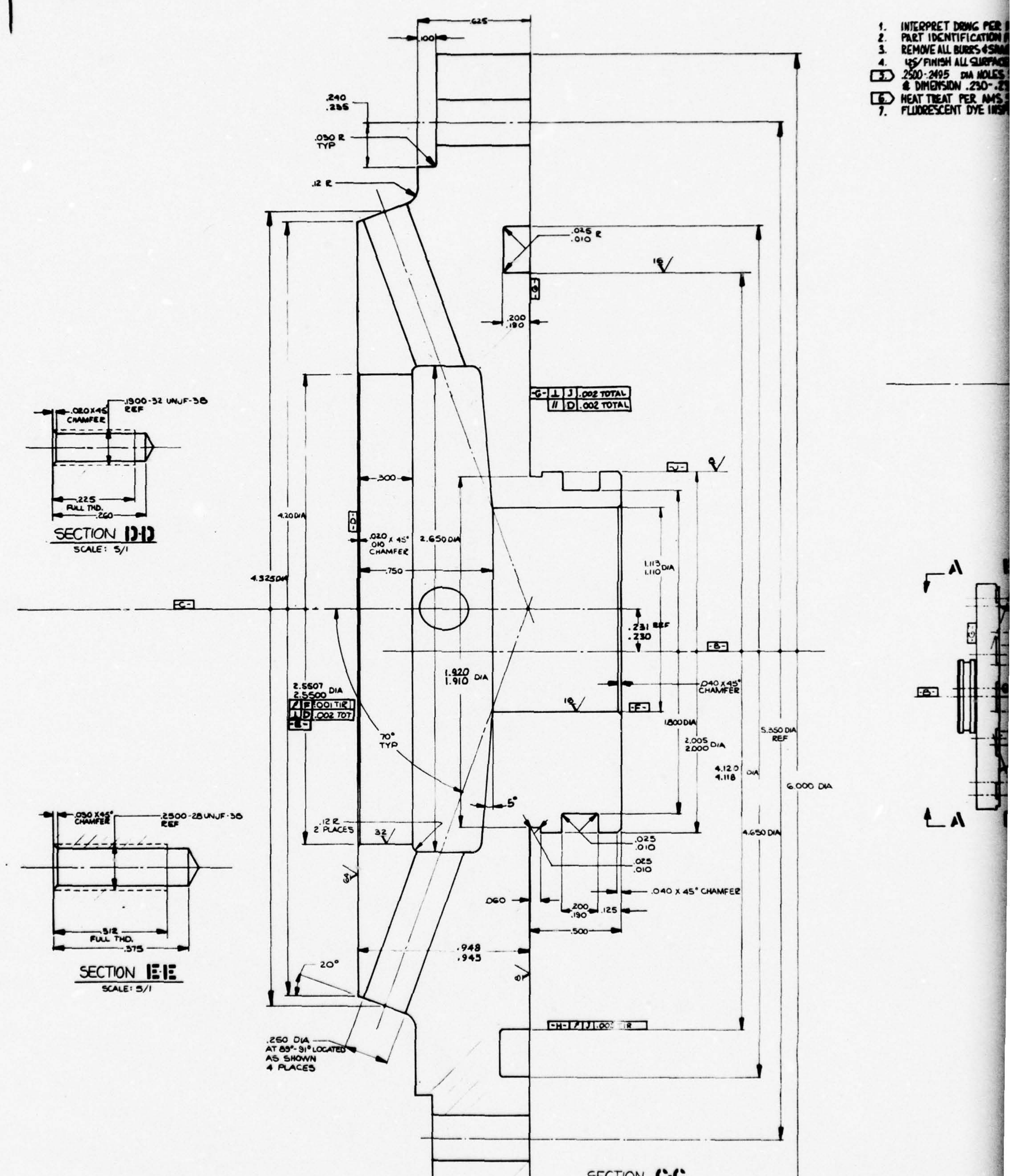


Figure 81. End Plat

1. INTERPRET DRWG PER MIL-STD-100B
2. PART IDENTIFICATION PER RRC-PS-0008
3. REMOVE ALL BURRS & SHARP EDGES PER R.06 EXCEPT AS NOTED
4. 125/ FINISH ALL SURFACES EXCEPT AS NOTED.
5. .2500-.2495 DIA HOLES SHALL BE USED TO ESTABLISH AXES -A- -B- -C- & DIMENSION .230-.231 THEN AFTER INSPECTION OPENED TO .261-.250 DIA.
6. HEAT TREAT PER AMS 5750
7. FLUORESCENT DYE INSPECT PER RRC-PS-0049.

2

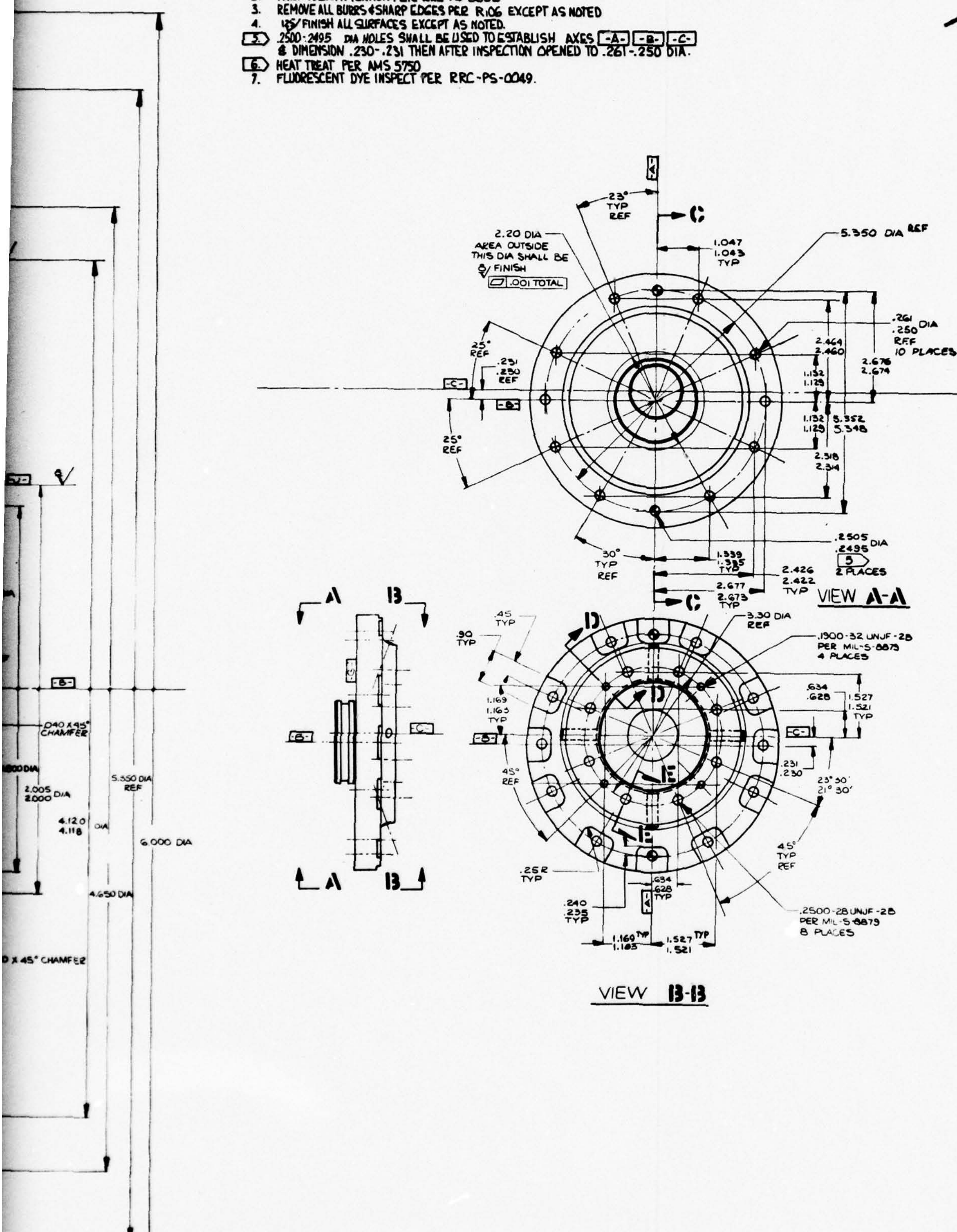


Figure 81. End Plate

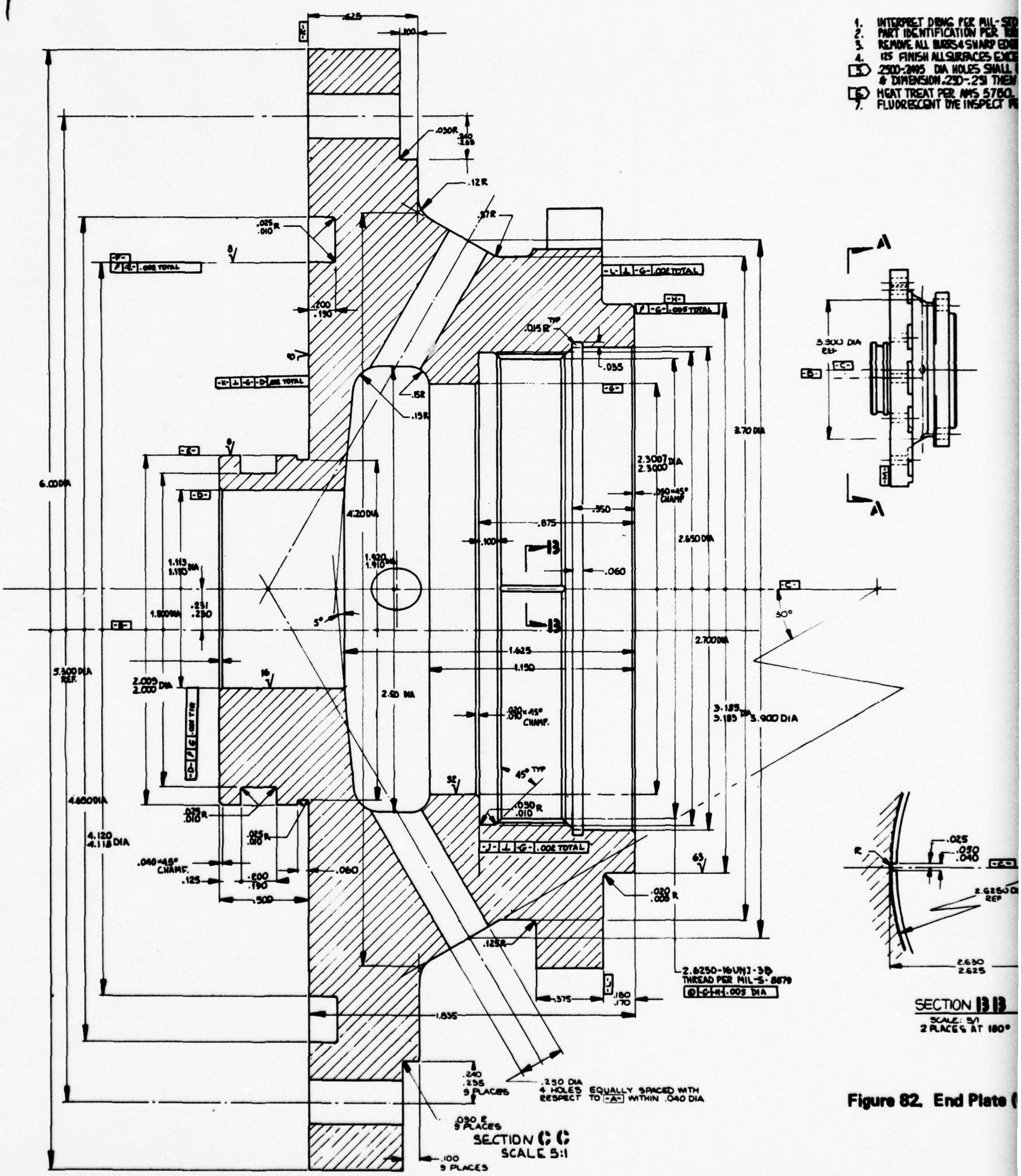


Figure 82. End Plate (

2

1. INTERPRET DWG PER MIL-STD-100B.
2. PART IDENTIFICATION PER RRC-PS-0008.
3. REMOVE ALL BURRS & SHARP EDGES PER R106 EXCEPT AS NOTED.
4. 125 FINISH ALL SURFACES EXCEPT AS NOTED.
5. .2500-.2495 DIA HOLES SHALL BE USED TO ESTABLISH AXES -A- -B- -C- & DIMENSION .230-.231 THEN AFTER INSPECTION OPENED TO .261-.250 DIA.
6. HEAT TREAT PER AMS 5750.
7. FLUORESCENT DYE INSPECT PER RRC-PS-0049.

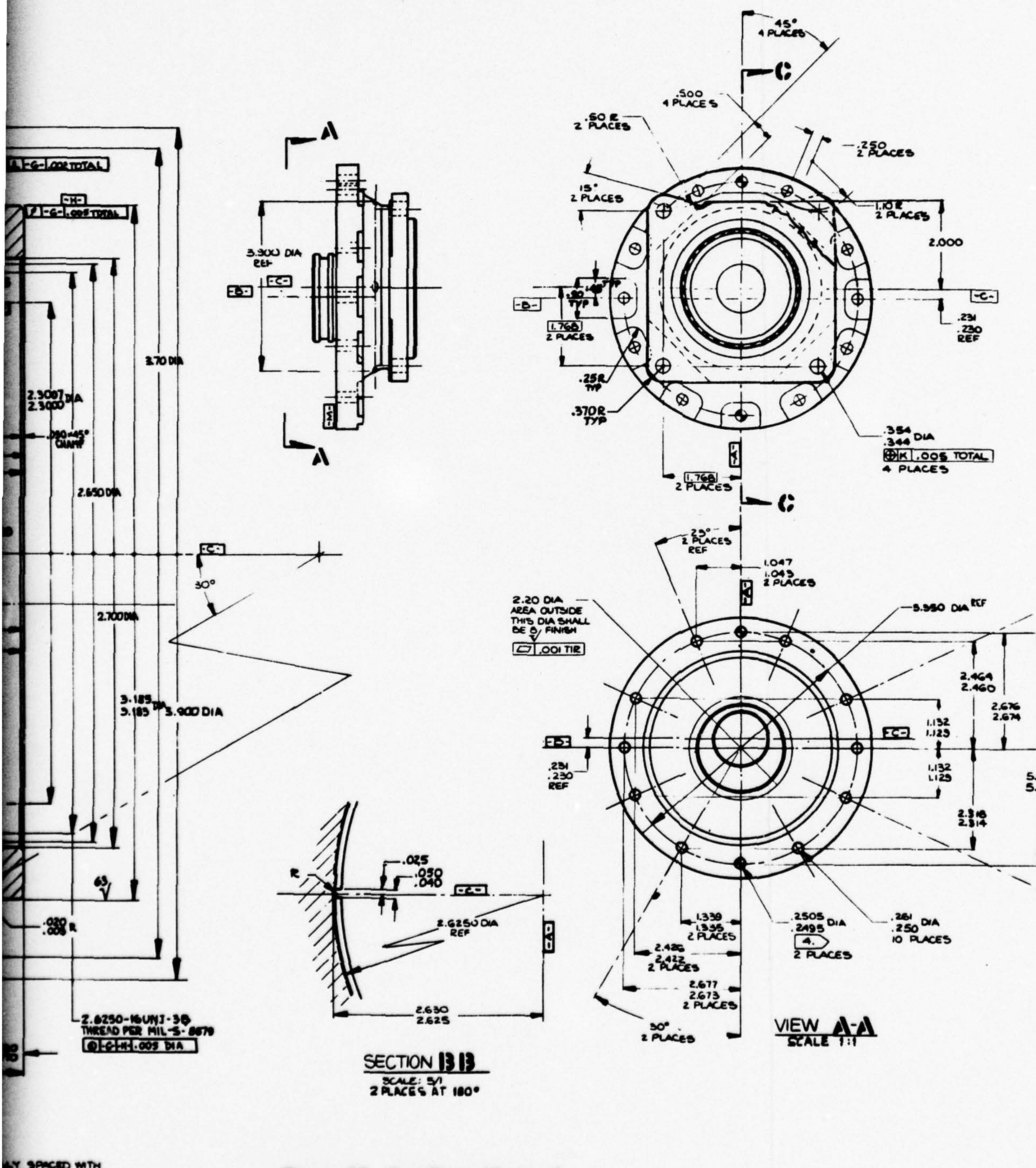


Figure 82. End Plate (Output)

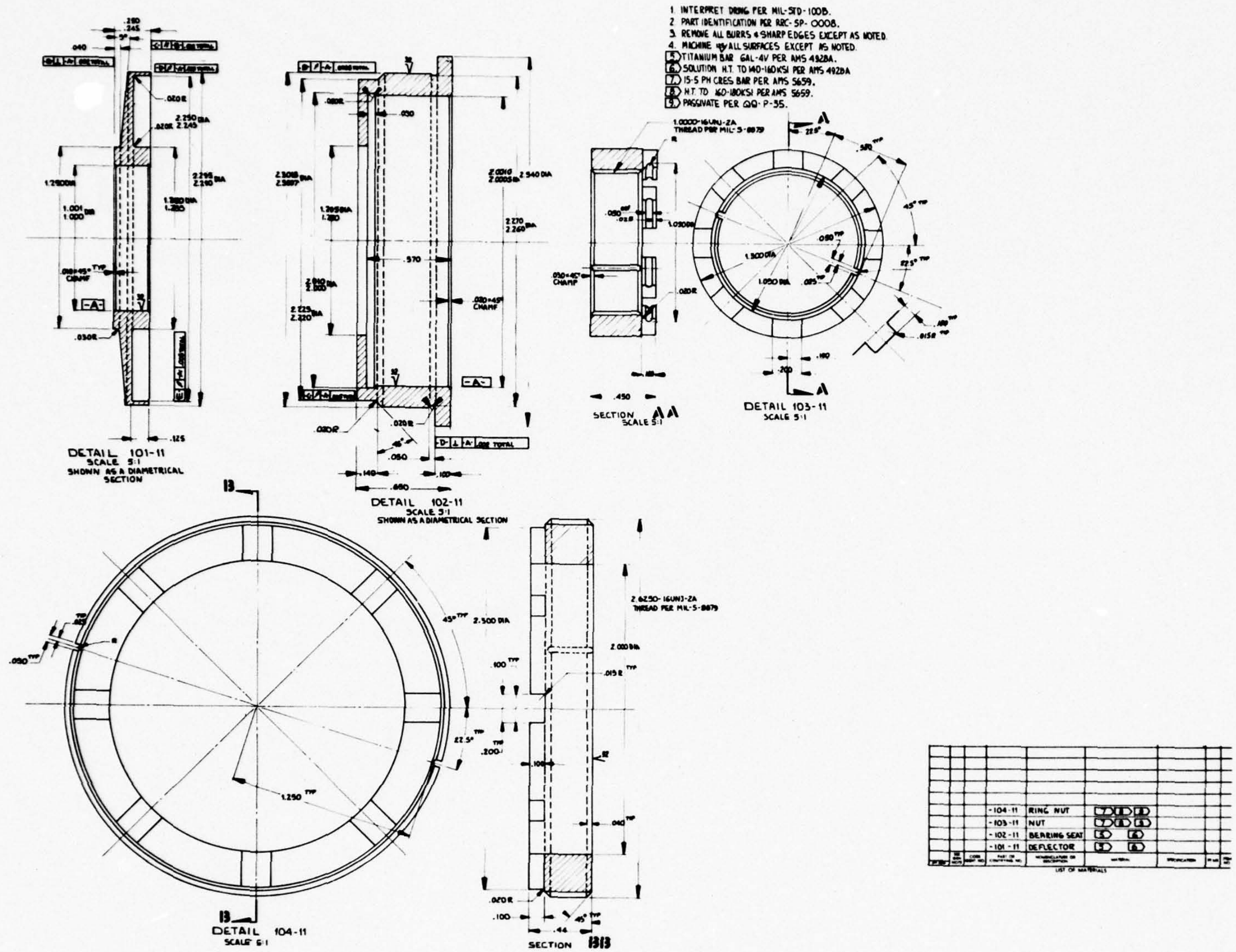


Figure 83. Bearing Retainer

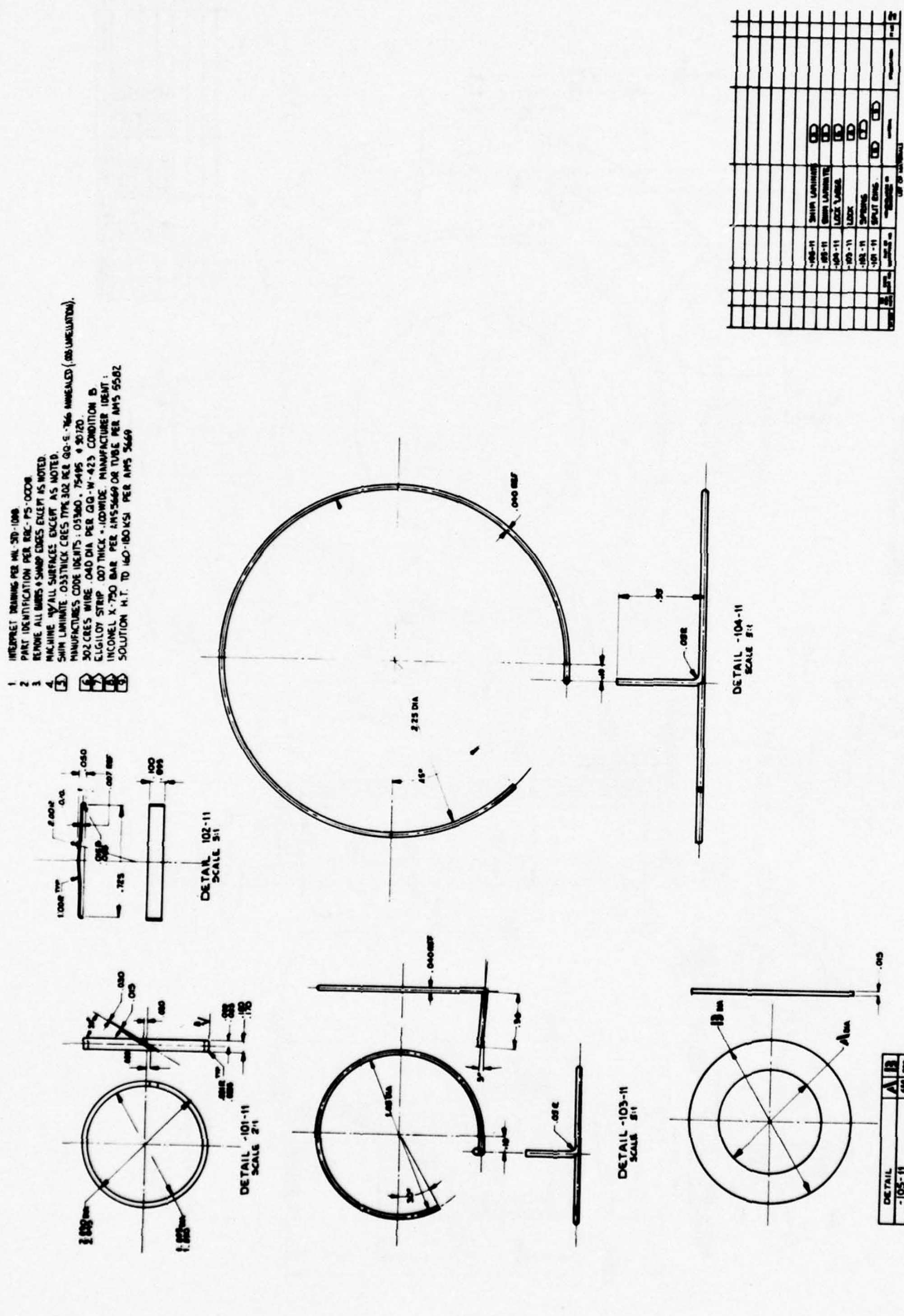


Figure 84. Shim and Spring

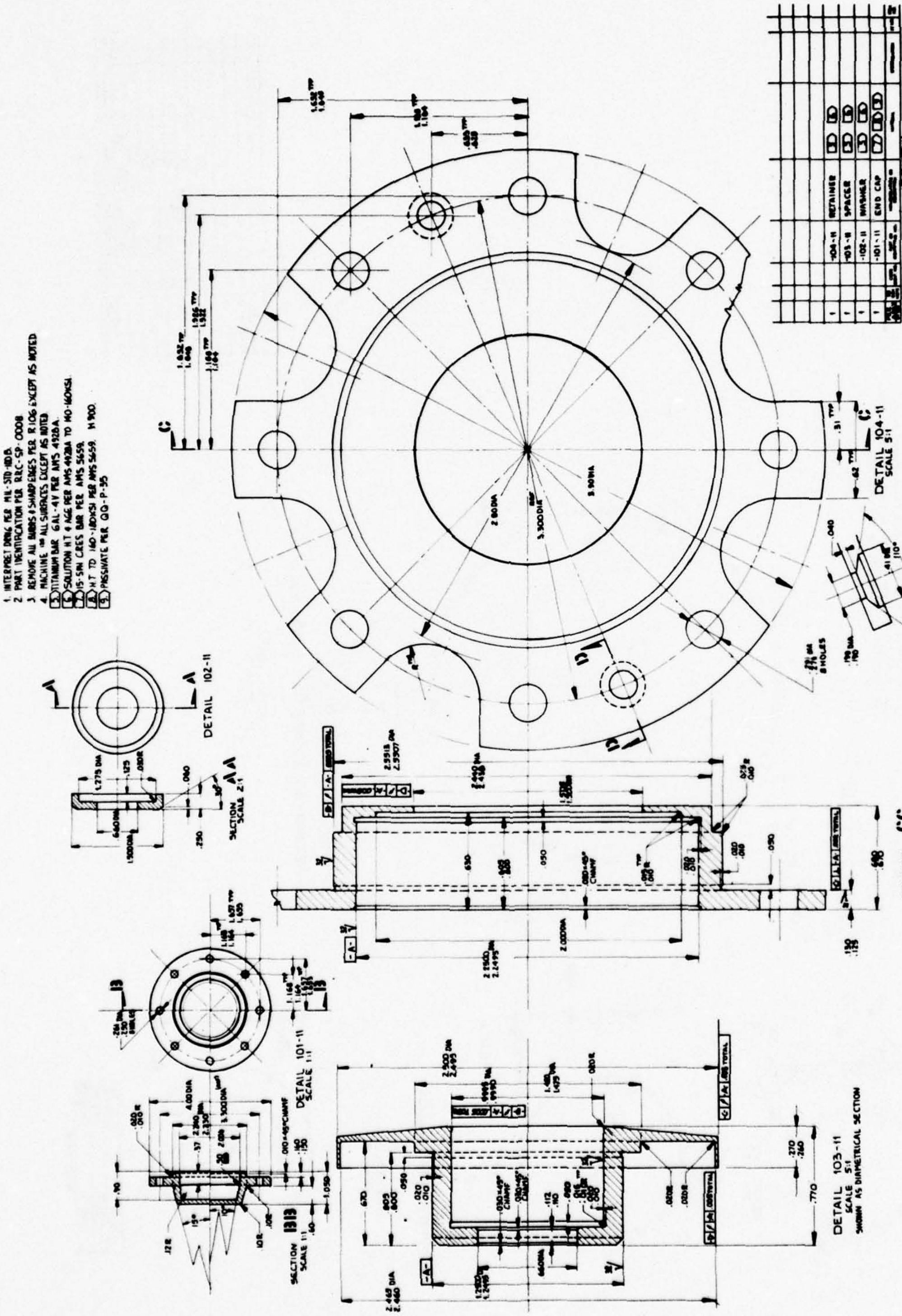
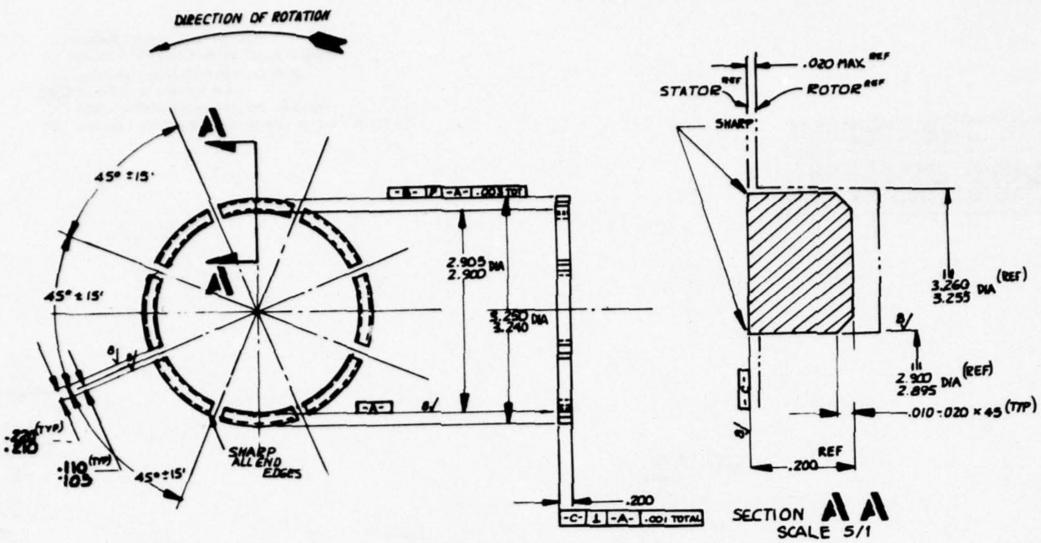


Figure 85. Bearing Retainer



<u>OPERATING CONDITIONS</u>

AMBIENT TEMP	-70 TO +130°F
OPERATING FLUID	HYDRAZINE
FLUID TEMPERATURE	1600°F MAX INLET
	900°F EXHAUST
FLUID PRESSURE	1000 PSI INLET
	130 PSI EXHAUST
OPERATING CYCLE	17 SECONDS
OPERATING R.P.M.S PER CYCLE	0 TO 4000
NORMAL NUMBER OF CYCLES	1
PERMISSIBLE NUMBER OF CYCLES WITH 10 SECS INTERVALS	5
LIFE NUMBER OF CYCLES	2000
MAXIMUM SPEED 5 SEC	6000RPMS
AVERAGE TEMP OF ROTOR	360°F
MAX TEMP OF ROTOR	500°F
ROTOR MATERIAL	CRES 15-5PH PER AMS 5659 (H900)
ROTOR SURFACE FINISH	8RMS
AVERAGE TEMP OF STATOR	350°F
MAX TEMPERATURE OF STATOR	500°F
STATOR MATERIAL	CRES 410 PER QQ-S-763 160-180 KSI
STATOR SURFACE FINISH	8RMS

FOR DISTRIBUTION OF TEMP & PRESSURES
SEE SK 5879

Figure 86. Rotor Seal

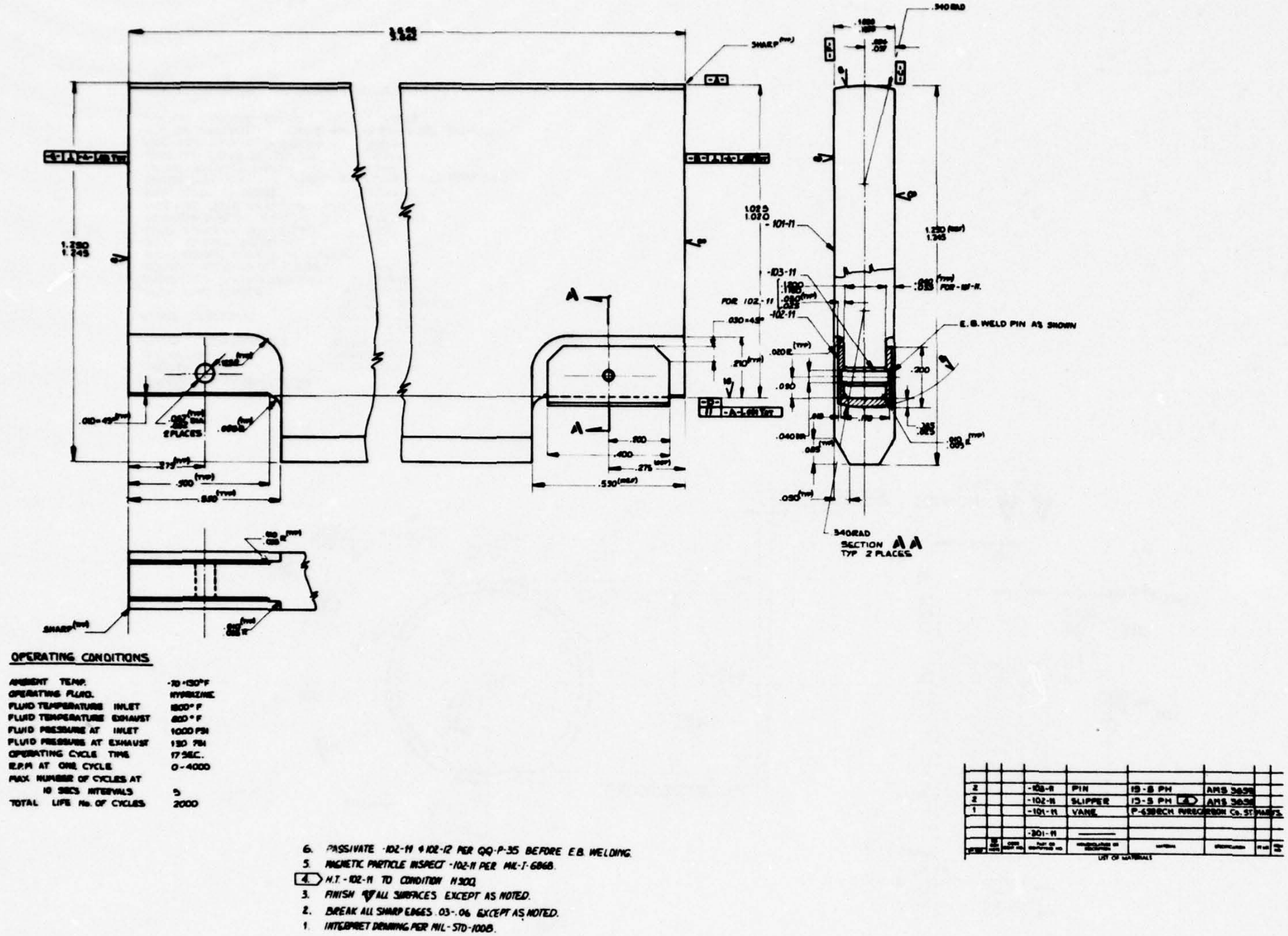


Figure 87. Vane Assembly

	PART NUMBER	PART NAME	MATERIAL PROTOTYPE	MATERIAL PRODUCTION	WEIGHT PROTO.	WEIGHT PROD.	CORROSION RESISTANCE	REMARKS
1	26651-101-11	ROTOR	RENE 41 BAR PER AMS5713		8.8 LBS	9.1 LBS	RENE 41 GOOD	
2	26652-101-11	STATOR	HASTELOY C SAND CASTING PER AMS5389		10.9 LBs	8.6 LBs	STELLITE GOOD	PRODUCTION MATERIAL : STELLITE CASTING
3	26653-101-11	END PLATE	HASTELOY C SAND CASTING PER AMS5389		5.3 LBs	4.5 LBs	"	" "
4	26654-101-11	END PLATE			7.1 LBS	6.4 LBS	"	" "
5	26656-101-11	DEFLECTOR	TITANIUM BAR 6AL-4V PER AMS4928B		.0330 LBs		GOOD	
6	26656-102-11	BEARING SEAT	TITANIUM BAR 6AL-4V PER AMS4928B		.1392 LBs			
7	26656-103-11	NUT	15-5PH CRES BAR PER AMS 5659		.2709 LBs			TITANIUM
8	26656-104-11	RING NUT	15-5PH CRES BAR PER AMS 5659		.2471 LBs			"
9	26657-101-11	SPLIT RING	INCONEL X-750 BAR PER AMS5669		.056 LBs			SET OF TWO
10	26657-102-11	SPRING	ELGILOY STRIP .007 × 100 × 1.000		.008 LBs			WEIGHT OF 16 UNITS
11	26657-103-11	LOCK	302 CRES WIRE PER QQ-W-423		.0011 LBs			
12	26657-104-11	LOCK LARGE	302 CRES WIRE PER QQ-W-423		.00249 LBs			
13	26657-105-11	SHIM	302 CRES SHIM LAMINATE		.0013 LBs			
14	26657-106-11	SHIM	302 CRES SHIM LAMINATE		.0034 LBs			
15	26658-101-11	END CAP	15-5PH CRES BAR PER AMS 5659		.5985 LBs			TITANIUM
16	26658-102-11	WASHER	TITANIUM BAR 6AL-4V PER AMS4928B		.0399 LBs			
17	26658-103-11	SPACER	TITANIUM BAR 6AL-4V PER AMS 4928B		.0072 LBs		GOOD	
18	26658-104-11	RETAINER	TITANIUM BAR 6AL-4V PER AMS 4928B		.2959 LBS			
19	26684-301-11	SEAL (SET)	REINFORCED CARBON		.105 LBS			TWO SETS OF EIGHT
20	26685-301-11	VANE ASSY	P-658RCH CARBON		.492 LBs			SET OF EIGHT
21	MS27641-20	BEARING			.22 LBS			POSSIBILITY OF STELLITE 6 BEARING
22	MS27641-26	BEARING			.26 LBS			POSSIBILITY OF STELLITE 6 BEARING
23	AND960-416L	WASHER			.375 LBS			
24	VS2627-4-16	BOLT						
25	VS324-B-10B	LOCK NUT						
26	VS324-B-04B	LOCK NUT						
					TOTAL	TOTAL		
					35.55	31.84		
					LBS	LBS		

Figure 88. Materials Summary Drawing (Including Parts List and Weight Summary)

SECTION V
SUMMARY

A detailed design of the hydrazine-fueled starter motor has been completed. Manufacturing drawings for each "make" item have been prepared, and all purchased "standards" have been identified.

Two computer models of the starter motor have been developed and utilized in support of the design analysis task a thermal-structural model and a thermal-performance model.

The thermal-structural model has been used to determine the temperature versus time characteristics of each starter motor component during typical starter operating sequences. A thorough understanding of the temperature history of each component is essential in selecting the proper materials of construction and establishing the proper clearances between moving parts for interference-free operation with minimum gas leakage.

The thermal-performance model has been used to verify the power output characteristics of the starter motor during various start and restart operating duty cycles at -65, +59 and +130°F ambient soak conditions, as discussed in the following subsections.

PROJECTED STARTER MOTOR PERFORMANCE

Figures 89 through 91 depict propellant consumption, propellant rate, motor inlet hot gas supply pressure, and the starter motor shaft speed as a function of time for "first-start" starter operation at -65, +59, and +130°F ambient soak conditions as predicted by the performance model.

The performance model accepts a certain assumed shaft load at any operating temperature. Figure 92 presents a typical shaft load input at the worst case (-65°F) APU start condition. For a given set of inlet gas supply parameters, the computer model is then capable of generating a starter output torque versus speed curve for the assumed load as shown in Figure 93.

The net torque available between the starter output characteristics and the starter load is used to generate the output shaft speed versus time curve as shown in Figure 94.

With the rotor speed known, the minimum gas consumption rate can be calculated based on the displacement of the motor. The total gas consumption requirement is the sum of the displaced volume and losses as shown in Figure 95. The computer program accounts for energy losses from gas leakage, vane friction, and heat transfer effects between the driving gas and the starter motor components. Figure 96 depicts a typical fuel consumption output trace from the computer model.

The thermal-performance model can be programmed to calculate starter performance parameters under multiple restart attempts at any ambient temperature condition. Figure 97 shows the effect

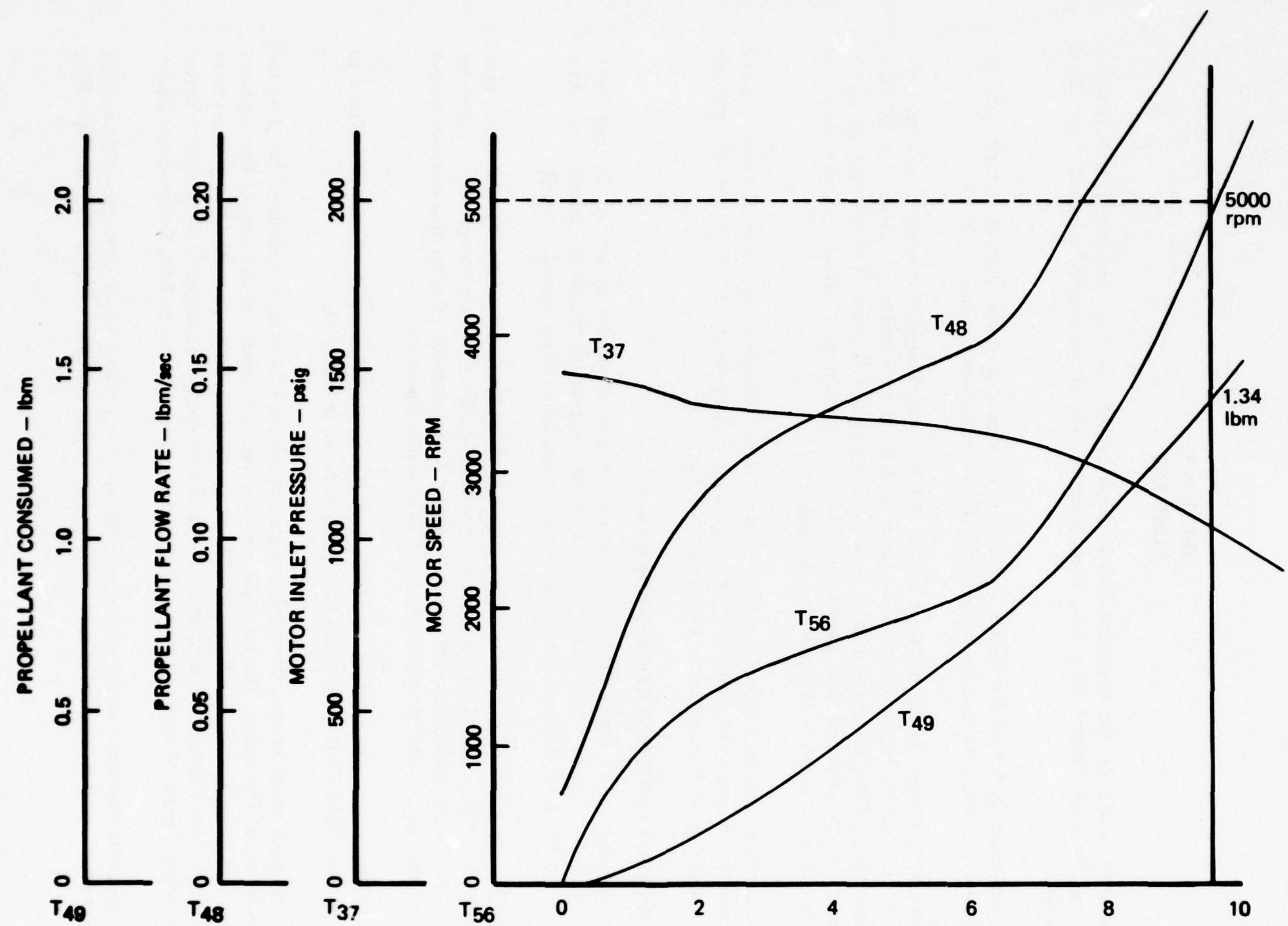


Figure 89. Projected Starter Performance
(Soak Temperature: -65°F ~ Duty Cycle: First Firing)

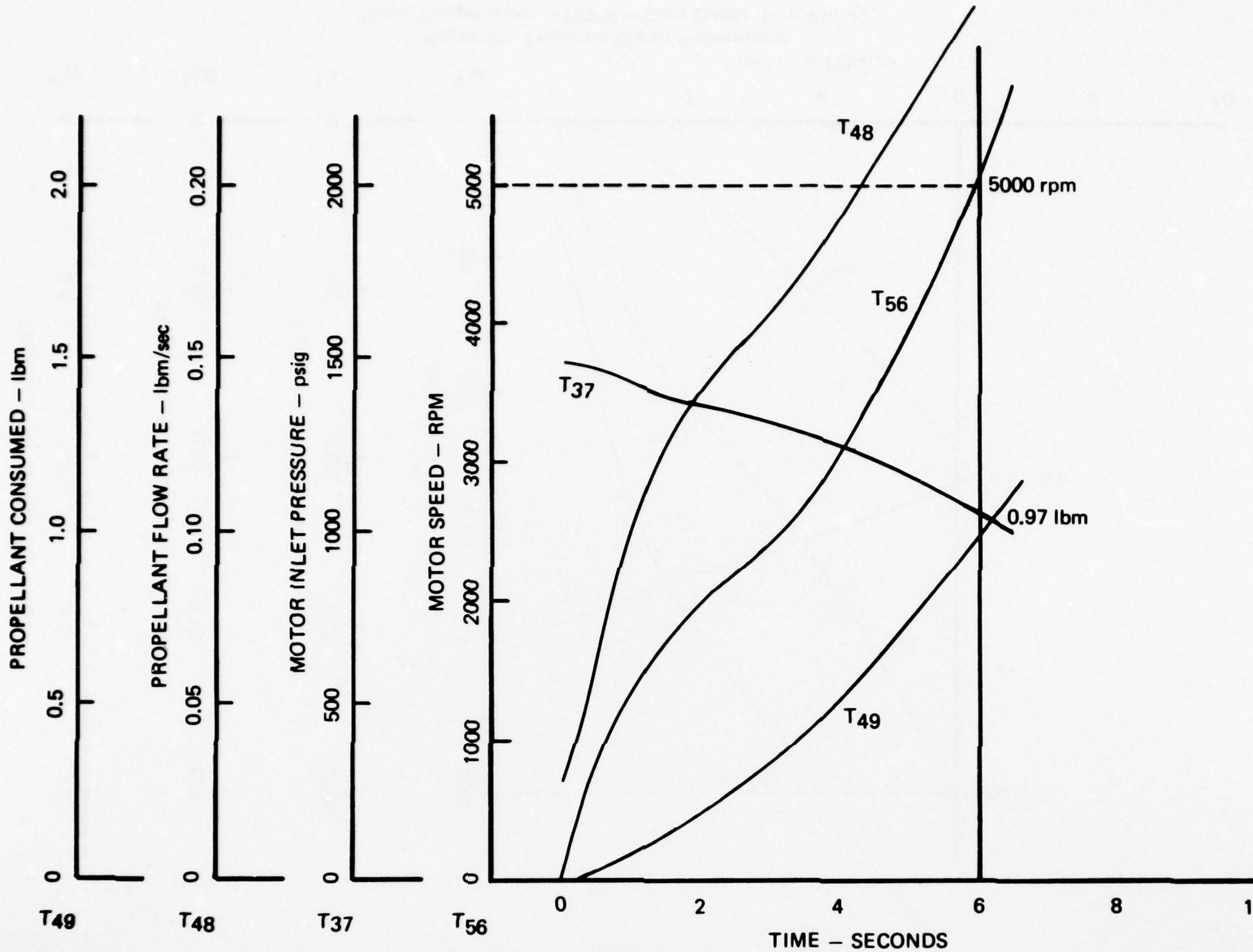


Figure 90. Projected Starter Performance
(Soak Temperature: +59°F ~ Duty Cycle: First Firing)

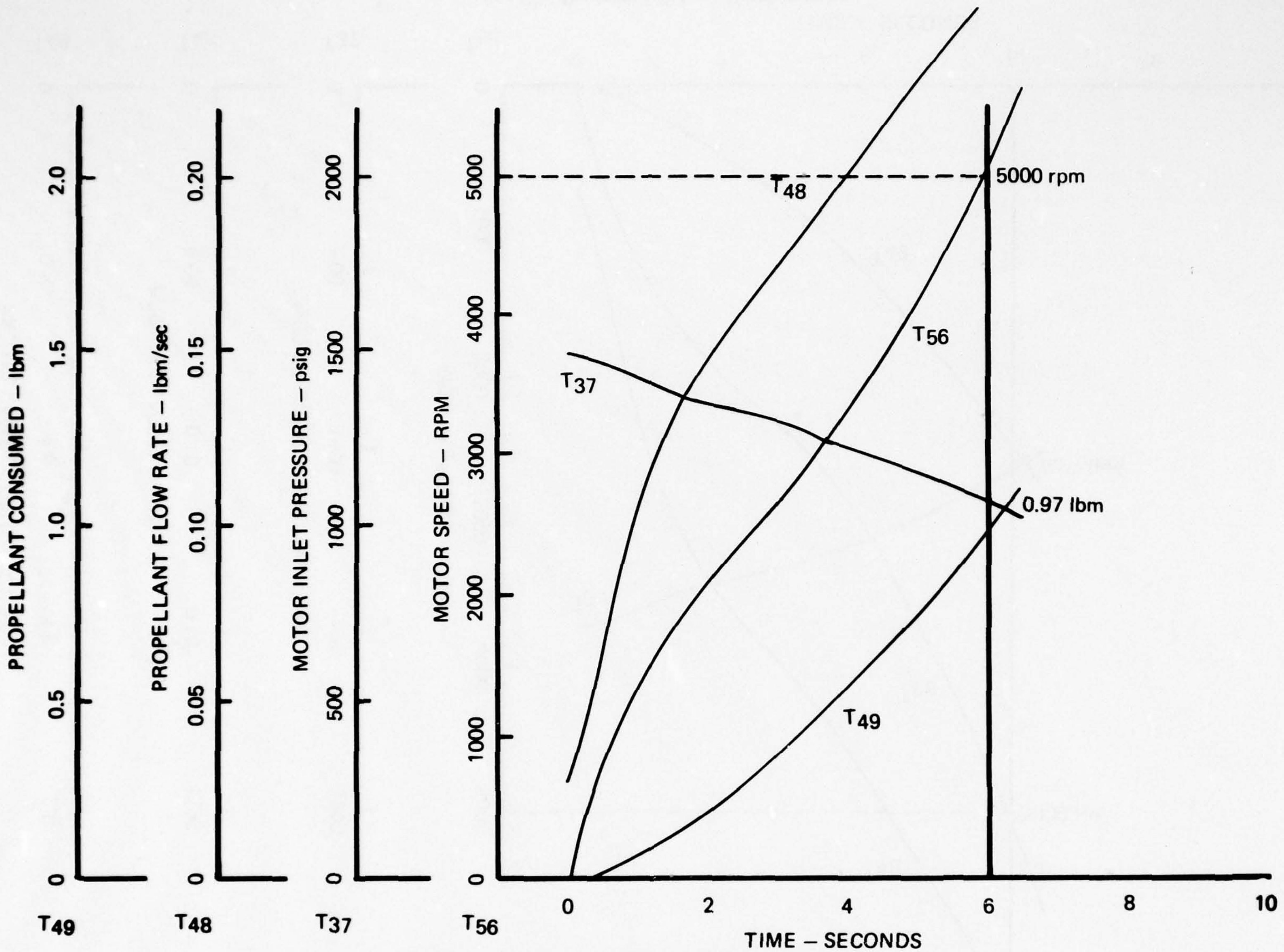


Figure 91. Projected Starter Performance
(Soak Temperature: +130°F ~ Duty Cycle: First Firing)

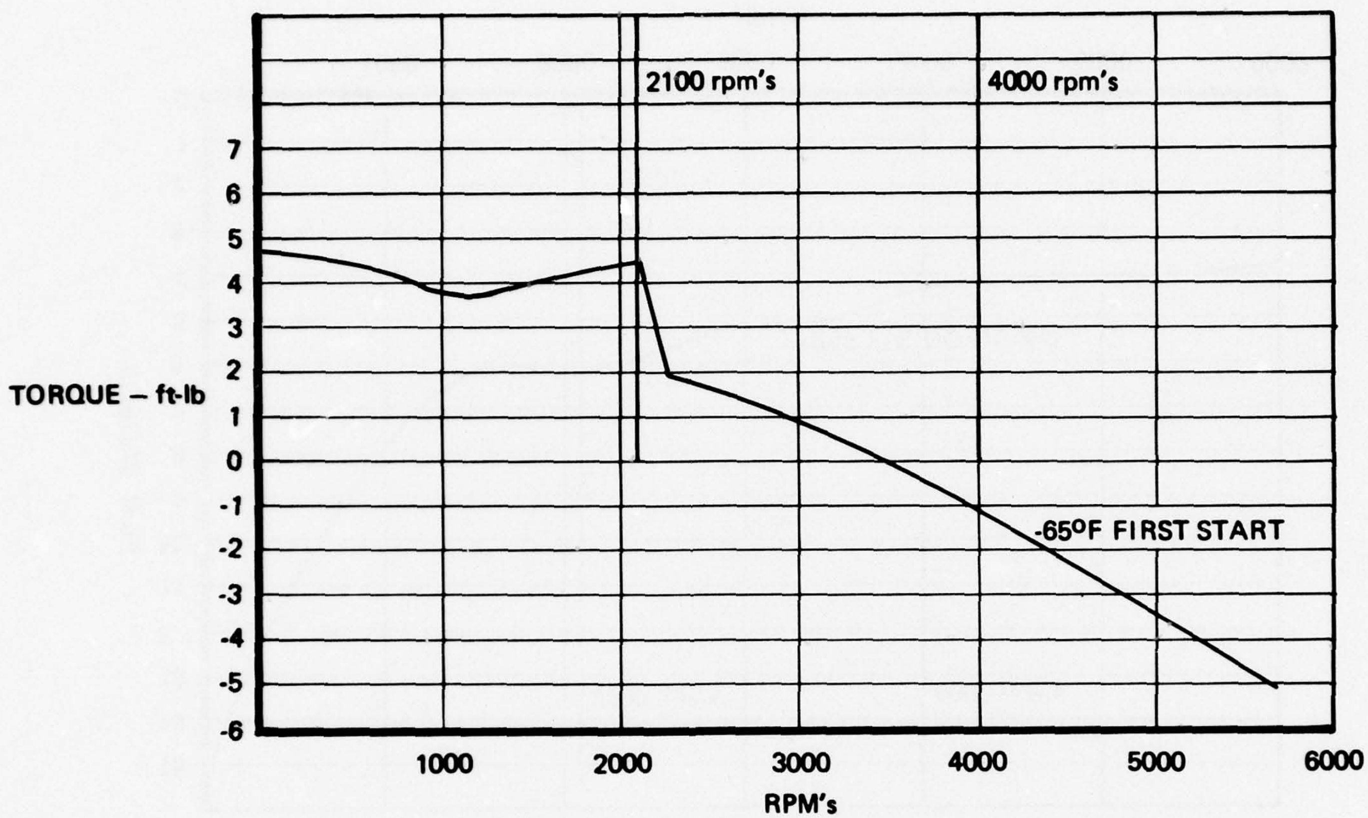


Figure 92. -65°F Starter Shaft Load

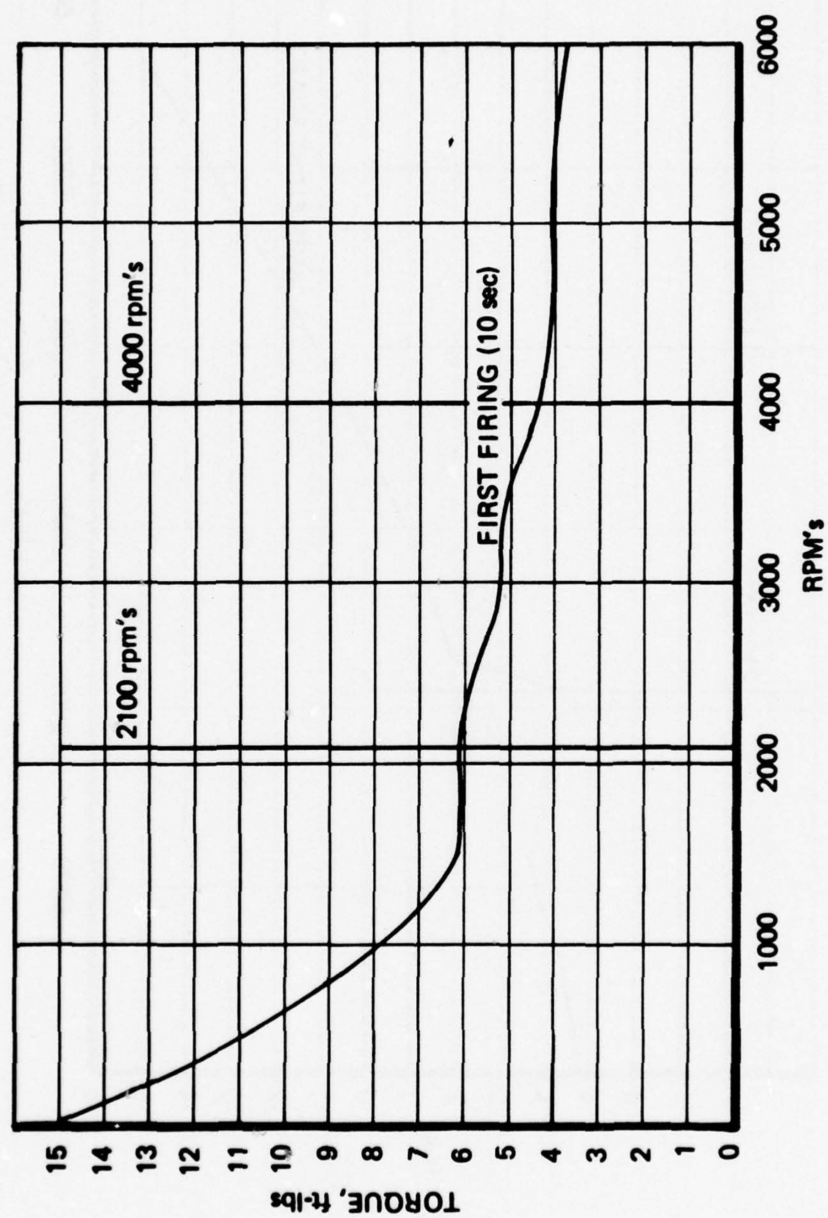


Figure 93. -65°F Starter Shaft Output

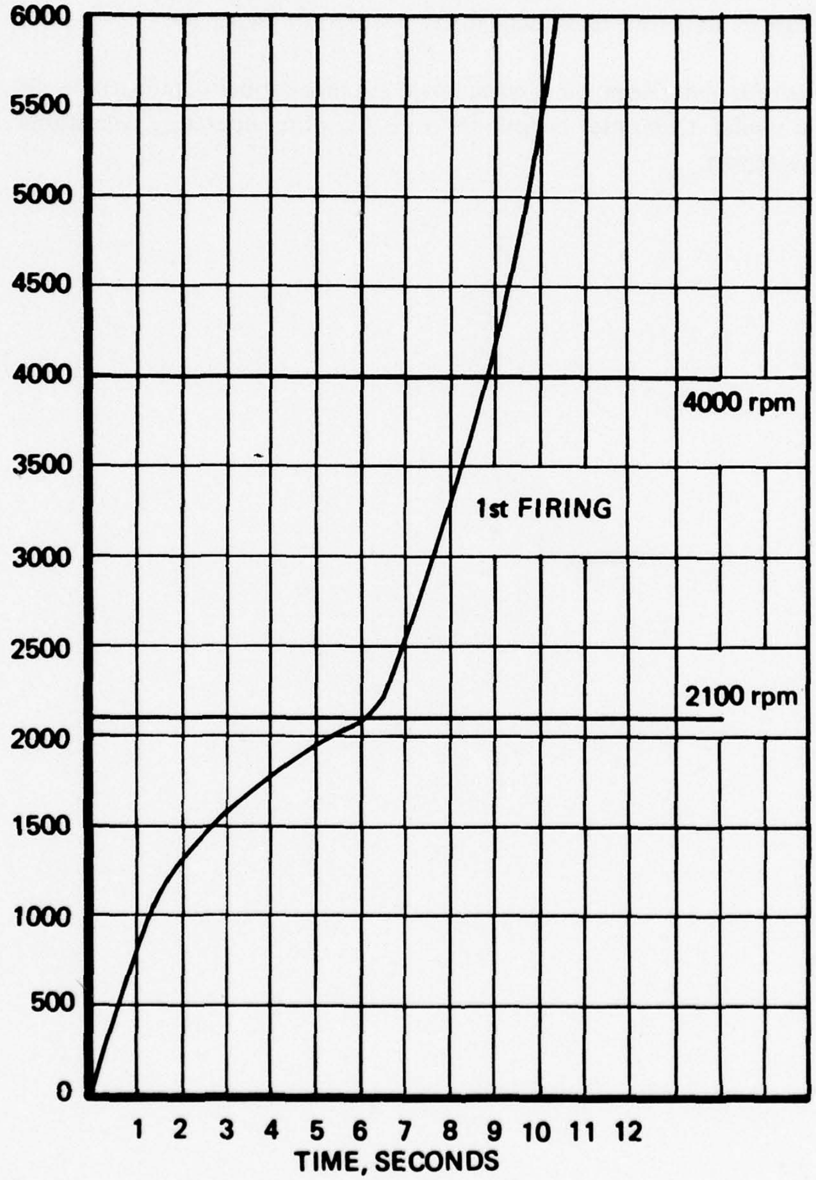


Figure 94. Starter Speed at -65^{o}F

on starter output torque of operating the starter through three full power, full duration start cycles at -65°F soak conditions with a 10-second delay between restarts. It is noted that the starter output torque increases significantly during each successive start cycle due primarily to a large reduction in thermal losses between the incoming hot gas and the mass of the starter components which are being heated during each start cycle. Fuel consumption is reduced during each successive start as shown in Figure 98, and the increase in output shaft torque available during each successive restart results in a decrease in start time as shown (for two starts) in Figure 99.

The computer output data from the thermal-performance model demonstrates the usefulness and flexibility of the model. Computer output tab runs for other operating conditions are presented in Section VI of this report.

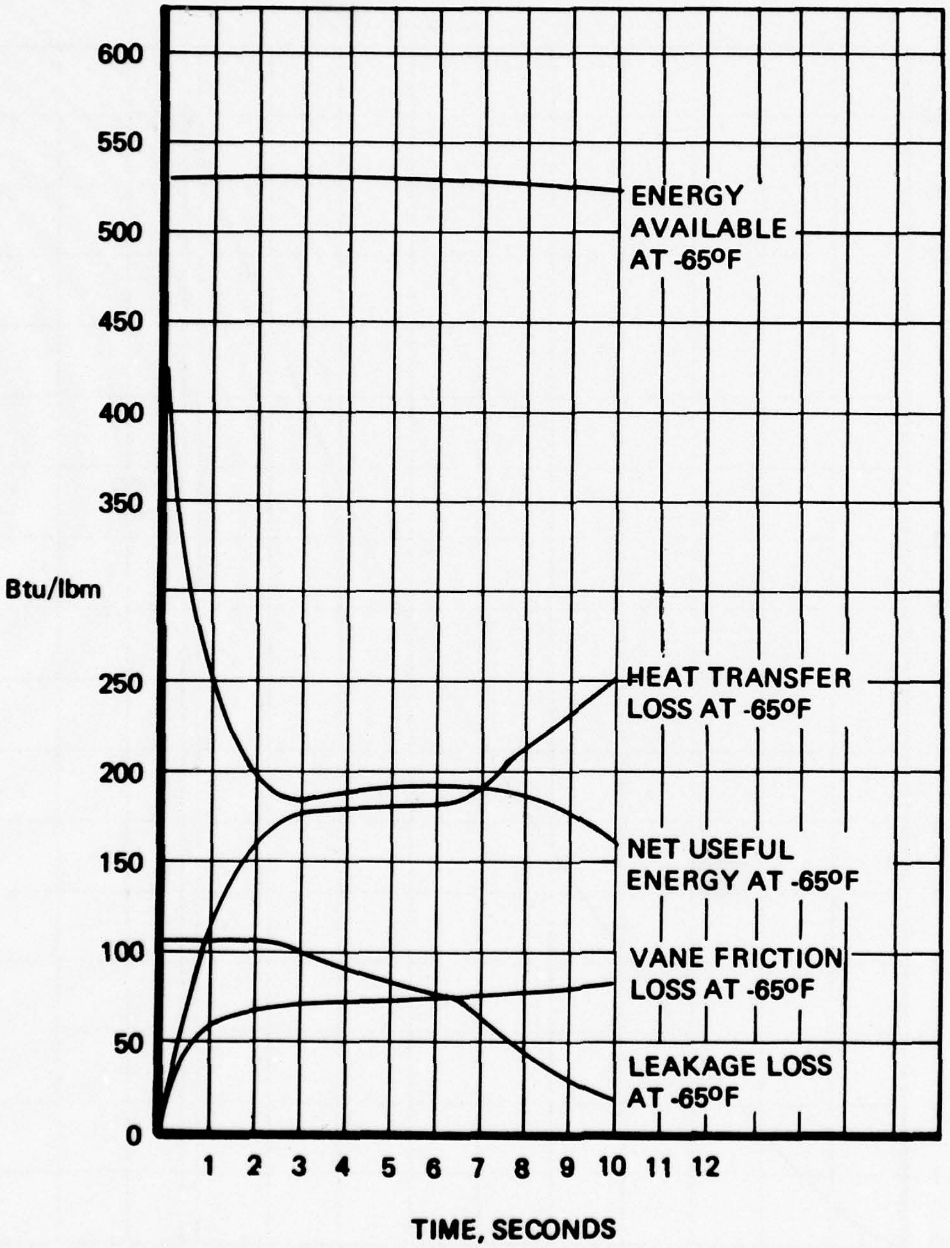


Figure 95. Starter Energy Balance – 1st Start at -65°F

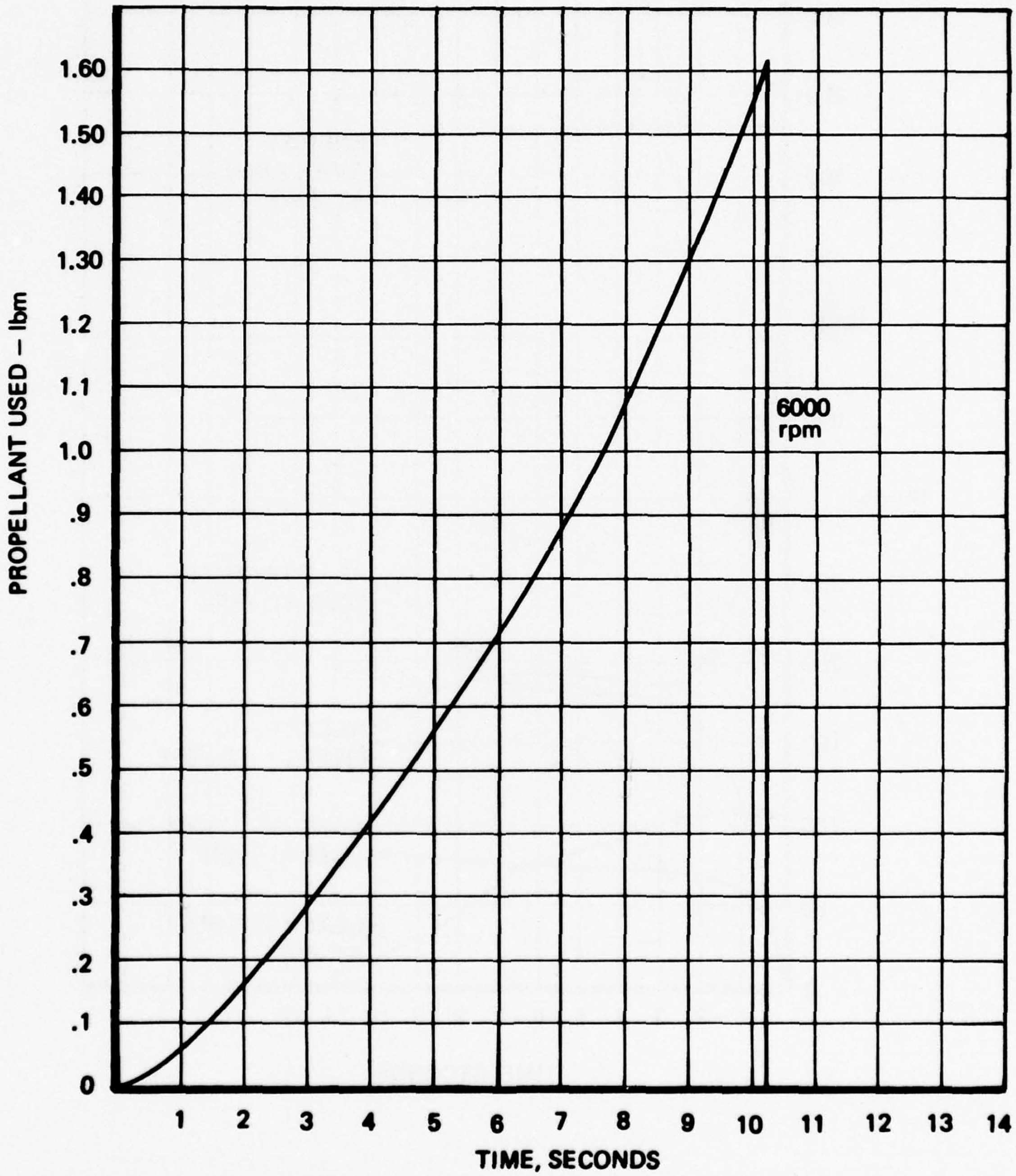


Figure 96. Propellant Consumption, 1st Start at -65°F

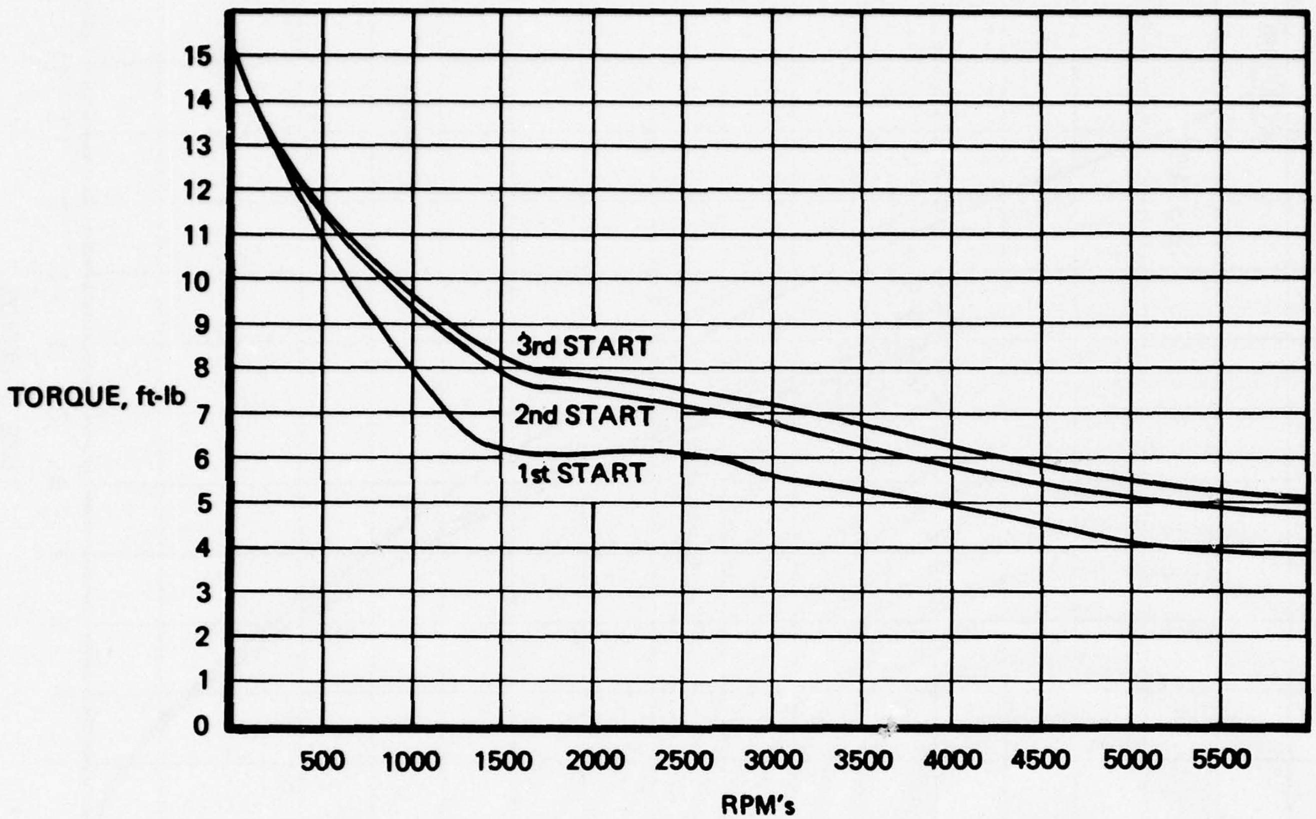


Figure 97. Starter Output Torque — 3 Starts at -65°F (10-Second Soak Between Starts)

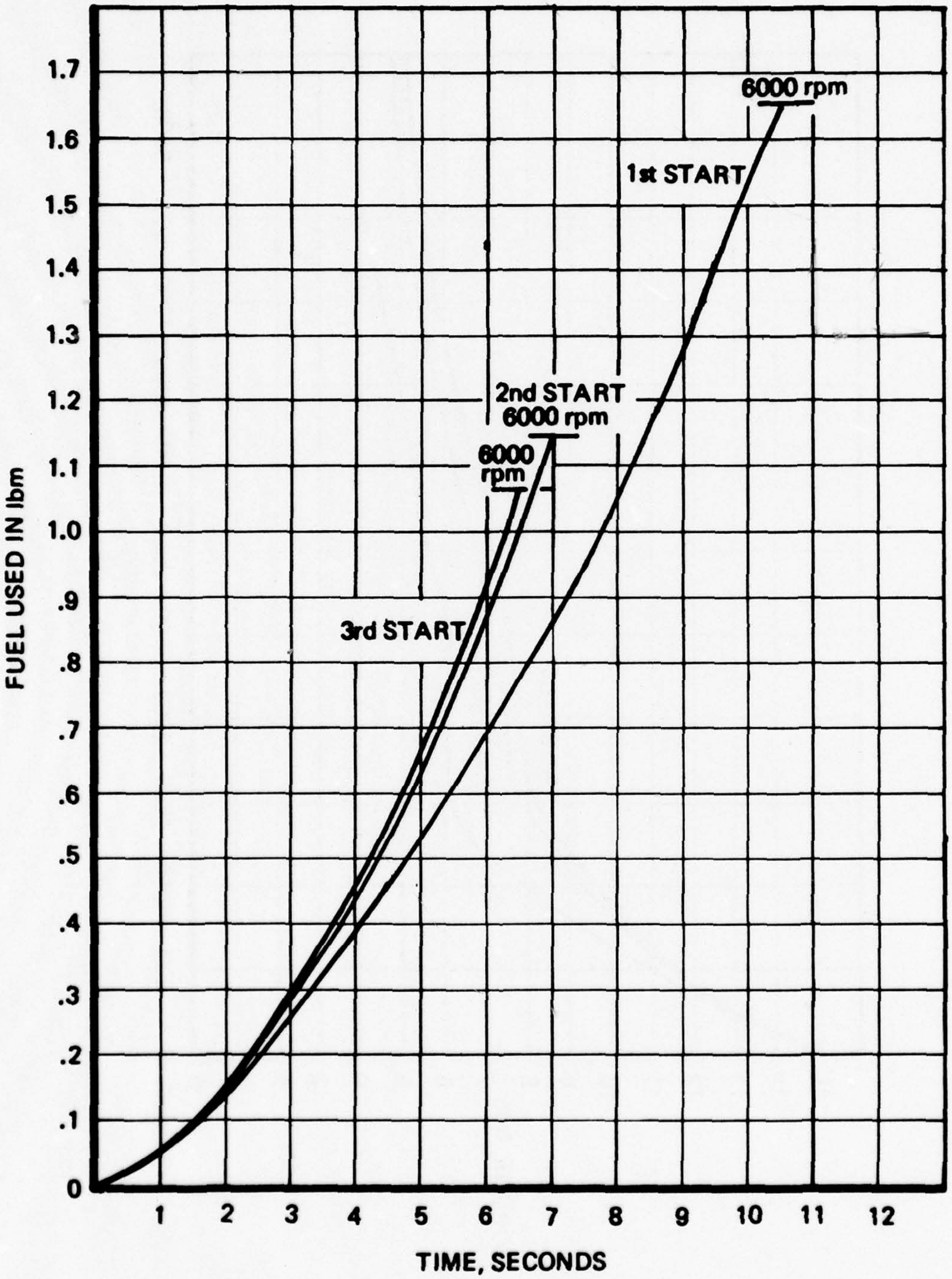


Figure 98. Starter Fuel Consumption – 3 Starts at -65°F (10-Second Soak Between Starts)

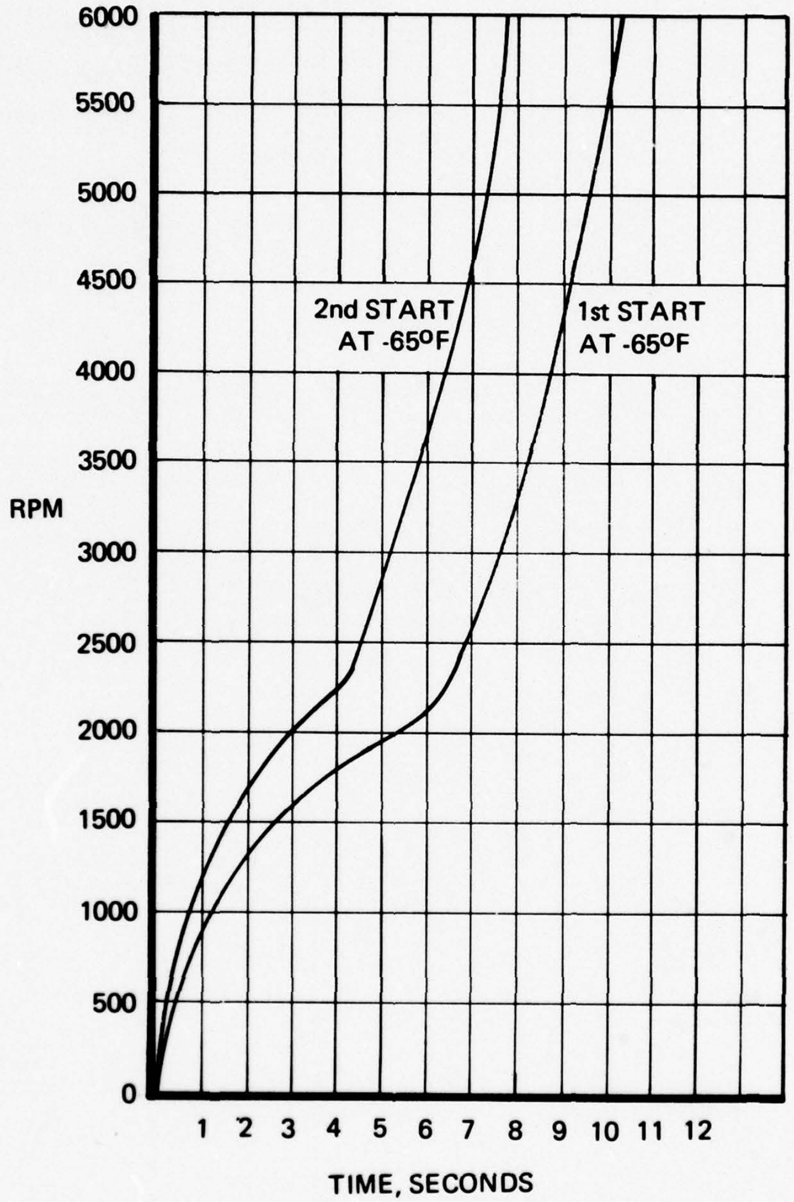


Figure 99. Starter Speed During Two Starts at -65°F (10 Seconds Between Starts)

SECTION VI
HOT GAS MOTOR PERFORMANCE
(START/RESTART)

This section presents computer print sheets depicting projected hot gas motor performance characteristics during first start and two subsequent restart operating cycles with a 10-second delay between the restart attempts. A total of nine computer runs is included to fully document operating characteristics at -65, +59 and +130°F ambient temperature operating conditions.

The computer print sheet format accommodates a print-out of 60 parameters at approximately 0.5-second intervals during hot gas motor operation. The output data is grouped in a 10 x 6 matrix as shown in Figure 100, which also includes parameters for each matrix location.

The computer was programmed to allow the starter to operate for approximately 12 seconds (0.0033 hour), maximum. The program stopped the fuel flow to the starter when the starter speed reached or exceeded 6,000 rpm (60,000 rpm APU speed). In all cases, terminal starter speed was achieved before the 12-second interval was completed. The heat transfer portion of the computer model continued to operate during the remainder of the 12-second start interval and the additional 10-second soak period that was allotted between restart attempts.

The nine computer runs are located as shown in Table 9.

COMPUTER RUN LOCATIONS

Ambient Soak Temperature, °F	1st Start	2nd Start	3rd Start
-65	Pages 139 through 143	Pages 145 through 147	Pages 149 through 151
+59	Pages 153 through 155	Pages 157 through 159	Pages 161 through 163
+130	Pages 165 through 167	Pages 169 through 171	Pages 173 through 175

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50
51	52	53	54	55	56	57	58	59	60

Parameters:

1) Ambient temperature-surrounds, °F
2) Motor mount base temperature, °F
3) Gas generator – gas temperature, °F
4), 5), 6) Control volume gas temperature, °F
7) Exhaust gas temperature, °F
8) Shaft temperature, °F
9) Rotor temperature, °F
10), 11) End plate temperature, °F
12), 13) Bearing temperature, °F
14), 15), 16), 17) Stator case temperature, °F
18) Exhaust flange temperature, °F
19–29) Not used

(See Figure 73)

30) Ambient temperature, °F
31) Hot gas specific heat capacity, Btu/lbm-°F x 100
32) Hot gas specific heat ratio x 10
33) Hot gas molecular weight – lbm/lbm mole
34) Initial volume – in.^{3} x 100
35) Volume ratio V_2/V_1 x 10
36) Hot gas supply pressure, psia
37) V_1 pressure, psia
38) V_2 pressure, psia
39) Ambient pressure, psia
40) Mass of gas used per revolution, lbm x 10,000
41) Cycle ideal energy available, Btu/lbm
42) Actual cycle efficiency, percent
43) Cycle useful energy available, Btu/lbm
44) Cycle leakage energy loss, Btu/lbm
45) Cycle heat transfer loss, Btu/lbm
46) Cycle vane friction loss, Btu/lbm
47) Leakage flow rate, lbm/sec x 100
48) Total flow rate, lbm/sec x 100
49) Total propellant expenditure, lbm x 100
50) Actual torque produced, ft-lbf
51) Required torque, ft-lbf
52) Margin allowance, percent
53) APU moment of inertia, lbf-sec^2-ft
54) Specific fuel consumption, lbm/hp-hr
55) Shaft work available out of gearbox, hp
56) Starter motor speed, rpm
57) Gearbox efficiency, percent
58) Gearbox ratio
59) Thermal efficiency, percent
60) Initial CV heat transfer coefficient, Btu/ft^2-hr-°F

Figure 100. Terminal Locations for Output Data

Table 9. 12-Second Firing Period Including Soakback Data (Half Sec PO)

TIME (HOURS)	MIN. RC PROD.=	AT NODE NO.	COMPUTING CYCLE	SYSTEM TEMPERATURES, DEG. F									
.0000	1.3888E-04	0	0	-65.0	-65.0	1591.2	763.1	349.1	142.0	-65.0	-65.0	-65.0	-65.0
				-65.0	-65.0	-65.0	-65.0	-65.0	-65.0	-65.0	-65.0	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1500.0	275.8	14.7	29.3
				528.2	79.4	419.3	105.6	3.3	.0	2.7	2.7	.0	15.2
				4.7	175.2	6.0	.0	.0	.0	85.0	10.0	.0	4.5
.0001	1.3888E-04	0	4	-65.0	-65.0	1591.2	1216.8	921.4	835.2	835.2	-65.0	-63.2	-65.0
				-65.0	-65.0	-65.0	-63.9	-64.6	-64.6	-64.8	-63.3	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1492.5	257.2	14.7	26.5
				528.1	65.6	346.5	105.6	41.1	34.9	2.6	4.4	1.0	11.4
				4.4	117.8	6.0	20.1	7.9	425.6	85.0	10.0	12.2	24.6
.0003	1.3888E-04	0	8	-65.0	-65.0	1591.2	1211.9	917.9	813.1	813.1	-65.0	-52.6	-64.8
				-64.8	-65.0	-65.0	-57.7	-61.9	-62.0	-63.5	-51.6	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1468.1	252.3	14.7	27.4
				528.0	50.3	265.7	105.6	99.8	56.9	2.6	7.5	4.2	9.0
				4.0	92.8	6.0	20.3	13.3	816.9	85.0	10.0	12.1	81.4
.0004	1.3888E-04	0	12	-65.0	-65.0	1591.2	1199.5	899.1	782.9	782.9	-65.0	-32.6	-64.4
				-64.4	-65.0	-65.0	-45.6	-57.0	-57.2	-61.1	-30.1	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1442.6	244.6	14.7	27.5
				527.8	42.5	224.2	105.6	134.0	64.1	2.5	9.6	8.6	7.6
				3.7	77.3	6.0	22.2	15.6	1109.4	85.0	10.0	11.1	137.0
.0006	1.3888E-04	0	16	-65.0	-65.0	1591.2	1189.9	884.6	761.2	761.2	-64.9	-5.3	-63.8
				-63.8	-65.0	-65.0	-28.8	-50.0	-50.5	-57.6	-1.1	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1420.0	238.2	14.7	27.3
				527.6	37.7	199.0	105.5	155.6	67.6	2.5	11.1	13.9	6.7
				3.8	49.0	6.0	24.1	16.6	1315.6	85.0	10.0	10.2	184.2
.0007	1.3888E-04	0	20	-65.0	-65.0	1591.2	1184.2	875.7	748.4	748.4	-64.8	26.8	-63.2
				-63.2	-65.0	-65.0	-8.4	-41.5	-42.6	-53.5	32.3	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1403.3	233.8	14.7	27.1
				527.5	35.0	184.7	105.5	167.9	69.4	2.4	12.1	19.8	6.2
				4.0	33.2	6.0	25.5	17.0	1456.5	85.0	10.0	9.6	218.6
.0008	1.3888E-04	0	24	-65.0	-65.0	1591.2	1175.5	861.1	730.9	730.9	-64.7	61.2	-62.4
				-62.4	-65.0	-65.0	14.1	-32.1	-33.8	-48.9	67.6	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1390.9	229.2	14.7	27.0
				527.4	34.8	183.7	98.9	174.2	70.6	2.4	12.8	26.0	6.1
				4.1	28.5	6.0	25.3	18.2	1569.3	85.0	10.0	9.7	245.2

Table 9. 12-Second Firing Period Including Soakback Data (Half Sec PO) (Continued)

TIME (HOURS)	MIN. RC PROD.=	AT NODE NO.	COMPUTING CYCLE	SYSTEM TEMPERATURES, DEG. F									
.0010	1.3888E-04	0	28	-65.0	-65.0	1591.2	1168.7	849.7	717.8	717.8	-64.5	97.0	-61.5
				-61.5	-65.0	-65.0	38.3	-22.0	-24.4	-43.8	103.6	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1379.9	225.4	14.7	26.8
				527.4	34.9	184.2	93.4	178.3	71.5	2.4	13.4	32.6	6.1
				4.1	25.4	6.0	25.0	19.3	1671.4	85.0	10.0	9.8	269.6
.0011	1.3888E-04	0	32	-65.0	-65.0	1591.2	1163.5	840.9	707.8	707.8	-64.2	133.6	-60.5
				-60.6	-65.0	-65.0	63.8	-11.3	-14.5	-38.4	139.8	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1369.6	222.2	14.7	26.6
				527.3	35.1	185.0	88.9	181.1	72.2	2.3	13.9	39.5	6.1
				4.2	23.0	6.0	24.6	20.3	1764.8	85.0	10.0	10.0	292.4
.0012	1.3888E-04	0	36	-65.0	-65.0	1591.2	1159.5	834.0	700.0	700.0	-63.9	170.4	-59.5
				-59.5	-65.0	-65.0	90.5	.0	-4.1	-32.7	175.6	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1360.0	219.5	14.7	26.4
				527.2	35.3	186.2	85.0	183.1	72.9	2.3	14.4	46.6	6.1
				4.3	21.0	6.0	24.3	21.4	1851.4	85.0	10.0	10.1	314.0
.0014	1.3888E-04	0	40	-65.0	-65.0	1591.2	1156.5	828.6	694.1	694.1	-63.6	207.2	-58.4
				-58.4	-65.0	-65.0	118.1	11.9	6.7	-26.6	210.8	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1350.9	217.1	14.7	26.3
				527.1	35.6	187.8	81.7	184.2	73.4	2.3	14.9	53.9	6.1
				4.3	19.4	6.0	23.9	22.4	1932.4	85.0	10.0	10.3	334.5
.0015	1.3888E-04	0	44	-65.0	-65.0	1591.2	1154.1	824.4	689.7	689.7	-63.2	243.6	-57.1
				-57.2	-64.9	-64.9	146.4	24.1	17.9	-20.2	245.0	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1342.3	215.0	14.7	26.1
				527.1	36.0	189.6	78.8	184.8	73.9	2.3	15.3	61.5	6.1
				4.4	18.2	6.0	23.6	23.3	2009.0	85.0	10.0	10.4	354.2
.0017	1.3888E-04	0	48	-65.0	-65.0	1591.2	1152.4	821.1	686.3	686.3	-62.7	279.3	-55.9
				-55.9	-64.9	-64.9	175.3	36.8	29.4	-13.5	278.0	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1334.1	213.2	14.7	26.0
				527.0	36.3	191.6	76.2	184.9	74.3	2.3	15.6	69.2	6.2
				4.5	17.2	6.0	23.2	24.3	2082.2	85.0	10.0	10.6	373.3
.0018	1.3888E-04	0	52	-65.0	-65.0	1591.2	1150.2	817.0	682.1	682.1	-62.2	314.2	-54.5
				-54.6	-64.9	-64.9	204.7	49.9	41.2	-6.6	309.6	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1326.1	211.2	14.7	25.7
				526.9	36.8	193.9	73.7	184.6	74.7	2.2	16.0	77.2	6.2
				2.8	85.8	6.0	22.6	25.6	2203.3	85.0	10.0	10.9	393.5

Table 9. 12-Second Firing Period Including Soakback Data (Half Sec PO) (Continued)

TIME (HOURS)	MIN. RC PROD.=	AT NODE NO.	COMPUTING CYCLE	SYSTEM TEMPERATURES, DEG. F									
.0019	1.3888E-04	0	56	-65.0	-65.0	1591.2	1136.1	792.9	654.7	654.7	-61.7	350.0	-52.9
				-53.1	-64.9	-64.9	236.4	64.1	53.8	1.0	340.6	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1300.4	203.2	14.7	25.0
				526.7	36.8	193.8	65.9	191.0	76.0	2.2	17.5	85.6	6.0
				1.5	241.2	6.0	22.1	28.4	2531.2	85.0	10.0	11.1	468.0
.0021	1.3888E-04	0	60	-65.0	-65.0	1591.2	1121.8	769.4	627.6	627.6	-61.1	388.7	-51.2
				-51.3	-64.8	-64.8	272.8	80.3	68.1	9.6	371.3	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1261.7	193.5	14.7	24.3
				526.4	36.0	189.4	58.0	201.7	77.3	2.1	19.0	94.8	5.7
				1.0	409.5	6.0	22.3	30.8	2885.5	85.0	10.0	11.1	564.9
.0022	1.3888E-04	0	64	-65.0	-65.0	1591.2	1109.0	748.4	603.6	603.6	-60.4	429.2	-49.1
				-49.3	-64.8	-64.8	313.8	98.6	83.9	19.3	400.7	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1220.0	183.9	14.7	23.5
				526.0	35.2	184.9	51.1	211.5	78.4	2.0	20.6	104.8	5.4
				.4	1164.9	6.0	22.5	33.0	3268.6	85.0	10.0	10.9	674.1
.0024	1.3888E-04	0	68	-65.0	-65.0	1591.2	1097.4	729.3	582.0	582.0	-59.7	470.4	-46.7
				-46.9	-64.8	-64.8	359.1	119.1	101.2	30.1	427.4	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1175.5	174.4	14.7	22.6
				525.6	34.4	180.6	45.2	220.4	79.4	1.9	22.1	115.6	5.1
				-.4	100.0	6.0	22.7	35.0	3689.7	85.0	10.0	10.8	797.2
.0025	1.3888E-04	0	72	-65.0	-65.0	1591.2	1085.9	710.3	560.9	560.9	-58.9	511.2	-44.0
				-44.2	-64.7	-64.7	408.5	141.7	119.9	42.0	450.3	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1126.7	164.5	14.7	21.7
				525.0	33.5	176.0	39.7	229.0	80.3	1.8	23.7	127.2	4.7
				-1.6	100.0	6.0	23.1	37.0	4183.6	85.0	10.0	10.7	943.4
.0026	1.3888E-04	0	76	-65.0	-65.0	1591.2	1074.1	690.9	539.5	539.5	-58.1	550.3	-40.8
				-41.1	-64.7	-64.7	461.8	166.4	140.1	55.2	468.2	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1071.6	153.8	14.7	20.6
				524.4	32.5	170.4	34.6	238.3	81.2	1.7	25.4	139.6	4.3
				-3.0	100.0	6.0	23.6	38.8	4768.8	85.0	10.0	10.4	1121.5
.0028	1.3888E-04	0	80	-65.0	-65.0	1591.2	1061.9	670.9	517.6	517.6	-57.2	586.4	-37.2
				-37.6	-64.6	-64.6	518.5	193.5	161.5	69.8	480.0	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1010.5	142.5	14.7	19.4
				523.6	31.2	163.6	29.8	248.2	81.9	1.5	27.2	152.8	3.9
				-4.6	100.0	6.0	24.3	40.2	5464.9	85.0	10.0	10.1	1338.4

Table 9. 12-Second Firing Period Including Soakback Data (Half Sec PO) (Continued)

TIME (HOURS)	MIN. RC PROD.= AT NODE NO.		COMPUTING CYCLE	SYSTEM TEMPERATURES, DEG. F									
.0000	1.3888E-04	0	0	-65.0	-65.0	1591.2	1030.9	678.6	491.2	303.7	-37.3	439.5	-19.4
				-21.7	-62.6	-62.6	492.6	206.7	161.2	100.6	444.7	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1500.0	275.8	14.7	29.3
				528.2	79.5	419.7	105.6	2.8	.0	2.7	2.7	.0	15.2
				4.7	175.5	6.0	.0	.0	.0	85.0	10.0	.0	4.7
.0001	1.3888E-04	0	4	-65.0	-65.0	1591.2	1226.2	935.4	853.6	853.6	-36.8	436.0	-18.9
				-21.3	-62.5	-62.6	491.1	206.7	161.0	101.2	444.2	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1492.4	259.8	14.7	26.5
				528.1	67.8	358.1	105.6	29.2	35.2	2.6	4.4	1.0	11.7
				4.4	124.9	6.0	19.2	8.3	438.0	85.0	10.0	12.8	24.9
.0003	1.3888E-04	0	8	-65.0	-65.0	1591.2	1233.2	950.2	856.1	856.1	-36.1	436.4	-18.2
				-20.6	-62.4	-62.5	492.2	208.4	162.5	103.1	448.5	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1466.1	257.9	14.7	27.3
				528.0	55.3	292.2	105.6	72.0	58.2	2.6	7.8	4.3	9.9
				3.9	113.2	6.0	17.9	15.7	888.0	85.0	10.0	13.8	88.7
.0004	1.3888E-04	0	12	-65.0	-65.0	1591.2	1226.5	939.6	835.6	835.6	-35.4	443.5	-17.1
				-19.7	-62.3	-62.4	497.6	212.4	166.2	106.1	458.5	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1434.0	250.3	14.7	27.2
				527.7	48.3	255.0	105.5	101.2	66.0	2.5	10.4	9.0	8.6
				3.7	94.7	6.0	18.9	19.9	1256.8	85.0	10.0	13.0	160.8
.0006	1.3888E-04	0	16	-65.0	-65.0	1591.2	1219.0	927.3	816.4	816.4	-34.7	456.4	-15.9
				-18.6	-62.2	-62.3	506.8	218.4	171.9	110.3	473.0	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1403.4	242.8	14.7	26.9
				527.5	44.1	232.6	104.3	120.9	69.7	2.4	12.3	14.8	7.8
				4.0	65.3	6.0	20.0	22.1	1529.9	85.0	10.0	12.3	225.6
.0007	1.3888E-04	0	20	-65.0	-65.0	1591.2	1203.3	900.4	784.2	784.2	-34.0	473.0	-14.5
				-17.3	-62.1	-62.2	518.9	226.0	179.0	115.3	489.4	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1378.4	233.9	14.7	26.6
				527.3	44.0	231.8	91.6	132.2	71.8	2.4	13.6	21.4	7.6
				4.2	55.4	6.0	19.6	25.1	1756.1	85.0	10.0	12.6	280.2
.0008	1.3888E-04	0	24	-65.0	-65.0	1591.2	1191.8	881.0	761.3	761.3	-33.3	492.0	-13.0
				-15.8	-61.9	-62.0	533.2	234.7	187.2	120.9	506.4	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1355.5	226.7	14.7	26.2
				527.2	43.9	231.3	82.5	140.1	73.3	2.3	14.8	28.6	7.5
				4.3	47.2	6.0	19.3	27.6	1956.7	85.0	10.0	12.8	331.4

Table 9. 12-Second Firing Period Including Soakback Data (Half Sec PO) (Continued)

TIME (HOURS)	MIN. RC PROD.=	AT NODE NO.	COMPUTING CYCLE	SYSTEM TEMPERATURES, DEG. F									
.0010	1.3888E-04	0	28	-65.0	-65.0	1591.2	1183.2	866.5	744.4	744.4	-32.5	512.6	-11.3
				-14.2	-61.8	-61.9	549.4	244.3	196.1	127.1	523.3	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1334.7	220.8	14.7	25.8
				527.0	43.8	230.8	75.8	146.0	74.4	2.3	15.8	36.3	7.4
				4.5	40.2	6.0	19.1	29.7	2133.7	85.0	10.0	12.9	378.5
.0011	1.3888E-04	0	32	-65.0	-65.0	1591.2	1169.1	842.1	716.7	716.7	-31.7	534.5	-9.4
				-12.5	-61.7	-61.8	567.6	255.0	206.0	133.8	539.6	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1309.5	212.7	14.7	25.1
				526.8	44.0	231.6	67.6	151.9	75.7	2.2	17.2	44.5	7.2
				1.6	283.9	6.0	18.5	33.5	2501.0	85.0	10.0	13.3	452.7
.0012	1.3888E-04	0	36	-65.0	-65.0	1591.2	1152.1	813.9	683.7	683.7	-30.8	559.2	-7.3
				-10.4	-61.6	-61.7	589.6	267.6	217.4	141.6	554.8	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1260.7	200.3	14.7	24.2
				526.4	43.1	226.7	57.5	164.8	77.4	2.1	19.2	53.7	6.8
				.9	533.6	6.0	18.5	37.3	2944.3	85.0	10.0	13.3	574.1
.0014	1.3888E-04	0	40	-65.0	-65.0	1591.2	1137.2	789.2	655.2	655.2	-30.0	586.2	-4.8
				-8.0	-61.4	-61.6	615.6	282.3	230.4	150.6	567.7	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1208.6	188.3	14.7	23.2
				525.9	42.1	221.3	49.3	176.6	78.7	2.0	21.1	63.9	6.4
				.2	2960.1	6.0	18.7	40.7	3421.0	85.0	10.0	13.2	711.8
.0015	1.3888E-04	0	44	-65.0	-65.0	1591.2	1123.5	766.6	629.5	629.5	-29.1	614.1	-1.9
				-5.3	-61.3	-61.4	645.3	299.0	244.9	160.7	577.3	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1153.6	176.5	14.7	22.2
				525.3	41.0	215.6	42.5	187.4	79.9	1.9	22.9	75.0	5.9
				-1.0	100.0	6.0	18.9	43.7	3952.1	85.0	10.0	13.0	868.4
.0017	1.3888E-04	0	48	-65.0	-65.0	1591.2	1109.8	744.3	604.4	604.4	-28.1	641.6	1.3
				-2.1	-61.2	-61.3	678.3	317.7	260.7	171.9	582.5	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1093.1	164.2	14.7	21.0
				524.6	39.9	209.1	36.4	198.3	80.9	1.7	24.8	87.1	5.4
				-2.4	100.0	6.0	19.2	46.5	4575.3	85.0	10.0	12.8	1057.0
.0018	1.3888E-04	0	52	-65.0	-65.0	1591.2	1095.9	721.9	579.6	579.6	-27.1	667.3	5.1
				1.5	-61.0	-61.2	714.4	338.2	277.6	184.3	582.1	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1026.7	151.4	14.7	19.7
				523.8	38.4	201.3	31.0	209.8	81.7	1.6	26.7	100.1	4.9
				-4.2	100.0	6.0	19.8	48.7	5309.6	85.0	10.0	12.4	1285.5

Table 9. 12-Second Firing Period Including Soakback Data (Half Sec PO) (Continued)

TIME (HOURS)	MIN. RC PROD.=	AT NODE NO.	COMPUTING CYCLE	SYSTEM TEMPERATURES, DEG. F									
.0000	1.3888E-04	0	0	-65.0	-65.0	1591.2	1073.2	738.9	551.7	364.5	-.6	462.3	33.9
				25.2	-55.1	-55.6	638.9	340.2	259.8	215.7	526.4	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1500.0	275.8	14.7	29.3
				528.2	79.5	419.8	105.6	2.7	.0	2.7	2.7	.0	15.2
				4.7	175.5	6.0	.0	.0	.0	85.0	10.0	.0	4.8
.0001	1.3888E-04	0	4	-65.0	-65.0	1591.2	1227.8	938.1	857.2	857.2	-.1	458.9	34.5
				25.7	-54.9	-55.5	636.9	340.0	259.3	216.1	525.8	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1492.4	260.3	14.7	26.5
				528.1	68.2	360.3	105.6	26.9	35.3	2.6	4.4	1.0	11.8
				4.4	126.2	6.0	19.0	8.4	440.4	85.0	10.0	13.0	25.0
.0003	1.3888E-04	0	8	-65.0	-65.0	1591.2	1237.0	956.6	864.8	864.8	.5	459.4	35.4
				26.4	-54.7	-55.3	636.8	341.0	260.1	217.5	529.1	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1465.7	259.0	14.7	27.2
				528.0	56.4	297.6	105.6	66.4	58.4	2.6	7.9	4.3	10.0
				3.9	117.4	6.0	17.5	16.2	902.0	85.0	10.0	14.1	90.2
.0004	1.3888E-04	0	12	-65.0	-65.0	1591.2	1231.6	948.2	847.0	847.0	1.2	466.7	36.5
				27.4	-54.5	-55.1	640.2	344.0	263.0	220.1	537.4	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1432.2	251.6	14.7	27.1
				527.7	49.6	261.7	105.5	94.1	66.3	2.5	10.6	9.1	8.8
				3.8	98.4	6.0	18.3	20.8	1286.3	85.0	10.0	13.5	165.7
.0006	1.3888E-04	0	16	-65.0	-65.0	1591.2	1222.8	933.6	825.4	825.4	1.9	480.0	37.9
				28.5	-54.3	-54.9	646.9	348.9	267.8	223.6	549.5	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1399.9	243.3	14.7	26.8
				527.5	45.9	242.3	102.0	113.1	70.1	2.4	12.5	15.0	8.1
				4.0	70.4	6.0	19.0	23.6	1575.9	85.0	10.0	12.9	234.5
.0007	1.3888E-04	0	20	-65.0	-65.0	1591.2	1207.0	906.7	793.4	793.4	2.6	497.0	39.4
				29.9	-54.1	-54.7	656.1	355.0	273.8	227.8	562.9	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1372.7	234.0	14.7	26.4
				527.3	46.0	242.4	88.8	123.8	72.2	2.4	14.0	21.7	7.9
				4.2	60.0	6.0	18.6	27.1	1823.0	85.0	10.0	13.2	294.6
.0008	1.3888E-04	0	24	-65.0	-65.0	1591.2	1195.5	887.2	770.5	770.5	3.3	516.6	41.1
				31.4	-53.8	-54.5	667.3	362.1	280.7	232.6	576.5	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1347.3	226.4	14.7	26.0
				527.1	45.9	242.2	79.5	131.6	73.8	2.3	15.2	29.1	7.8
				4.4	50.9	6.0	18.3	29.9	2042.7	85.0	10.0	13.4	351.6

Table 9. 12-Second Firing Period Including Soakback Data (Half Sec PO) (Continued)

TIME (HOURS)	MIN. RC PROD.=	AT NODE NO.	COMPUTING CYCLE	SYSTEM TEMPERATURES, DEG. F									
.0010	1.3888E-04	0	28	-65.0	-65.0	1591.2	1185.1	869.5	750.1	750.1	4.0	538.0	42.9
				33.0	-53.6	-54.3	680.2	370.1	288.4	238.0	589.7	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1324.3	219.6	14.7	25.5
				526.9	46.0	242.2	72.3	137.4	75.0	2.2	16.3	37.0	7.7
				1.9	250.5	6.0	17.8	33.0	2321.6	85.0	10.0	13.8	407.5
.0011	1.3888E-04	0	32	-65.0	-65.0	1591.2	1166.6	838.3	714.3	714.3	4.8	561.8	45.0
				34.9	-53.4	-54.0	695.7	379.3	297.3	244.0	601.7	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1280.6	207.4	14.7	24.5
				526.5	45.7	240.6	61.2	147.9	76.8	2.1	18.4	45.8	7.3
				1.2	426.0	6.0	17.5	37.9	2779.5	85.0	10.0	14.0	525.7
.0012	1.3888E-04	0	36	-65.0	-65.0	1591.2	1150.6	811.9	683.8	683.8	5.7	588.8	47.4
				37.1	-53.1	-53.8	714.8	390.4	307.6	251.0	611.7	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1226.3	194.6	14.7	23.5
				526.1	44.8	235.8	51.8	160.1	78.3	2.0	20.5	55.7	6.9
				.4	1287.7	6.0	17.6	42.0	3273.4	85.0	10.0	14.0	666.0
.0014	1.3888E-04	0	40	-65.0	-65.0	1591.2	1136.2	788.5	657.1	657.1	6.5	617.4	50.1
				39.7	-52.9	-53.6	737.1	403.1	319.3	259.0	618.4	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1169.1	182.1	14.7	22.4
				525.5	43.9	230.5	44.2	171.2	79.6	1.9	22.5	66.6	6.4
				-.6	100.0	6.0	17.7	45.6	3813.6	85.0	10.0	13.9	825.0
.0015	1.3888E-04	0	44	-65.0	-65.0	1591.2	1122.2	765.9	631.7	631.7	7.4	646.3	53.3
				42.7	-52.6	-53.4	762.5	417.3	332.1	268.0	620.9	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1107.1	169.3	14.7	21.2
				524.8	42.8	224.6	37.7	181.9	80.6	1.8	24.4	78.4	5.9
				-2.1	100.0	6.0	17.9	49.0	4443.0	85.0	10.0	13.7	1014.3
.0017	1.3888E-04	0	48	-65.0	-65.0	1591.2	1108.2	743.4	606.8	606.8	8.4	673.9	56.9
				46.1	-52.4	-53.1	790.4	433.1	345.9	277.8	618.1	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	1039.0	156.0	14.7	19.9
				524.0	41.5	217.4	31.9	193.1	81.6	1.6	26.4	91.2	5.4
				-3.8	100.0	6.0	18.3	51.9	5183.5	85.0	10.0	13.4	1243.8
.0018	1.3888E-04	0	52	-65.0	-65.0	1591.2	1093.7	720.6	582.1	582.1	9.4	698.3	61.0
				50.1	-52.1	-52.9	820.3	450.0	360.4	288.6	609.4	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	-65.0
				62.2	12.4	16.4	56.7	39.1	1500.0	965.8	142.2	14.7	18.5
				522.9	39.9	208.7	26.8	205.0	82.4	1.5	28.4	105.1	4.8
				-5.9	100.0	6.0	18.9	54.1	6059.3	85.0	10.0	13.0	1521.8

Table 9. 12-Second Firing Period Including Soakback Data (Half Sec PO) (Continued)

TIME (HOURS)	MIN. RC PROD.= AT NODE NO.		COMPUTING CYCLE	SYSTEM TEMPERATURES, DEG. F									
.0000	1.3888E-04	0	0	59.0	59.0	1621.5	840.2	449.6	254.3	59.0	59.0	59.0	59.0
				59.0	59.0	59.0	59.0	59.0	59.0	59.0	59.0	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1500.0	266.0	14.7	27.3
				561.4	79.4	445.9	112.3	3.2	.0	2.7	2.7	.0	15.1
				.0	100.0	6.0	.0	.0	.0	85.0	10.0	.0	4.5
.0001	1.3888E-04	0	4	59.0	59.0	1621.5	1205.2	878.2	782.9	782.9	59.0	61.3	59.0
				59.0	59.0	59.0	60.4	59.5	59.5	59.3	61.1	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1490.9	245.2	14.7	24.0
				561.3	63.2	354.9	112.3	47.2	46.9	2.6	5.3	1.1	10.6
				.5	1532.7	6.0	16.0	11.9	693.0	85.0	10.0	17.0	40.2
.0003	1.3888E-04	0	8	59.0	59.0	1621.5	1196.8	872.4	754.0	754.0	59.0	77.5	59.3
				59.3	59.0	59.0	70.5	63.4	63.2	61.1	77.7	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1446.5	236.9	14.7	25.2
				561.0	45.5	255.3	112.2	124.6	68.9	2.5	9.7	5.2	8.0
				1.5	343.9	6.0	18.9	18.5	1283.3	85.0	10.0	14.4	148.8
.0004	1.3888E-04	0	12	59.0	59.0	1621.5	1180.0	847.7	717.4	717.4	59.1	106.8	59.9
				59.9	59.0	59.0	89.4	70.7	69.8	64.5	106.8	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1405.5	225.9	14.7	25.0
				560.7	37.9	212.4	111.2	162.4	74.7	2.4	12.3	10.9	6.6
				2.1	160.9	6.0	21.7	20.3	1661.0	85.0	10.0	12.5	240.0
.0006	1.3888E-04	0	16	59.0	59.0	1621.5	1156.1	808.5	671.0	671.0	59.1	143.6	60.7
				60.7	59.0	59.0	114.2	80.0	78.1	68.8	141.6	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1374.5	214.3	14.7	24.6
				560.5	37.0	207.5	95.1	180.4	77.4	2.4	13.9	17.6	6.3
				2.6	109.1	6.0	21.7	23.0	1944.7	85.0	10.0	12.5	310.9
.0007	1.3888E-04	0	20	59.0	59.0	1621.5	1140.7	783.7	642.5	642.5	59.3	184.5	61.6
				61.6	59.0	59.0	143.2	90.9	87.6	73.8	178.8	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1348.4	206.1	14.7	24.3
				560.2	36.6	205.1	84.9	191.1	79.1	2.3	15.2	25.0	6.2
				2.9	79.2	6.0	21.6	25.2	2178.2	85.0	10.0	12.6	372.5
.0008	1.3888E-04	0	24	59.0	59.0	1621.5	1130.7	767.5	624.2	624.2	59.5	227.6	62.7
				62.6	59.0	59.0	175.4	102.9	97.9	79.3	216.5	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1326.2	200.1	14.7	23.9
				560.1	36.5	204.2	77.9	197.8	80.2	2.2	16.1	32.8	6.1
				3.2	60.1	6.0	21.5	27.1	2371.8	85.0	10.0	12.6	425.8

Table 9. 12-Second Firing Period Including Soakback Data (Half Sec PO) (Continued)

TIME (HOURS)	MIN. RC PROD.=	AT NODE NO.	COMPUTING CYCLE	SYSTEM TEMPERATURES, DEG. F									
.0010	1.3888E-04	0	28	59.0	59.0	1621.5	1121.2	751.5	606.7	606.7	59.7	271.5	63.9
				63.8	59.0	59.0	209.9	115.9	108.9	85.4	253.4	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1307.5	194.7	14.7	23.5
				559.9	36.6	205.2	72.3	201.3	81.2	2.2	17.1	41.2	6.0
				1.0	429.6	6.0	20.9	29.3	2633.4	85.0	10.0	13.0	478.0
.0011	1.3888E-04	0	32	59.0	59.0	1621.5	1104.8	724.9	576.9	576.9	60.1	317.4	65.3
				65.2	59.0	59.0	248.6	130.4	121.0	92.2	289.7	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1269.5	184.9	14.7	22.8
				559.5	36.2	202.4	63.1	211.3	82.7	2.1	18.7	50.2	5.7
				.6	694.7	6.0	20.9	32.3	3027.2	85.0	10.0	13.0	584.8
.0012	1.3888E-04	0	36	59.0	59.0	1621.5	1090.5	702.2	551.8	551.8	60.5	365.4	66.9
				66.8	59.1	59.1	292.2	146.8	134.3	99.8	324.6	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1227.2	175.3	14.7	22.0
				559.1	35.5	198.5	55.5	221.2	83.9	2.0	20.3	60.1	5.4
				.2	1764.9	6.0	21.0	34.8	3431.1	85.0	10.0	12.9	701.2
.0014	1.3888E-04	0	40	59.0	59.0	1621.5	1078.7	683.3	531.4	531.4	60.9	413.6	68.8
				68.7	59.1	59.1	340.1	164.8	148.6	108.2	356.5	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1184.4	166.5	14.7	21.3
				558.7	35.0	195.3	49.2	229.1	85.0	1.9	21.8	70.8	5.2
				-.3	100.0	6.0	21.1	37.2	3852.5	85.0	10.0	12.9	825.8
.0015	1.3888E-04	0	44	59.0	59.0	1621.5	1067.7	665.6	512.5	512.5	61.5	460.6	71.0
				70.9	59.1	59.1	391.7	184.5	164.0	117.5	384.3	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1139.3	157.6	14.7	20.5
				558.2	34.5	192.5	43.7	236.1	85.9	1.8	23.3	82.1	4.9
				-1.2	100.0	6.0	21.2	39.6	4331.5	85.0	10.0	12.8	967.8
.0017	1.3888E-04	0	48	59.0	59.0	1621.5	1056.8	648.0	493.9	493.9	62.1	505.0	73.5
				73.4	59.1	59.1	446.4	205.8	180.2	127.6	407.0	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1089.3	148.4	14.7	19.6
				557.5	33.9	189.0	38.5	243.3	86.8	1.7	24.9	94.3	4.6
				-2.4	100.0	6.0	21.3	41.9	4886.3	85.0	10.0	12.7	1136.4
.0018	1.3888E-04	0	52	59.0	59.0	1621.5	1045.1	629.2	474.3	474.3	62.7	545.5	76.4
				76.2	59.2	59.2	503.9	228.7	197.1	138.5	423.3	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1033.8	138.4	14.7	18.5
				556.8	33.2	184.6	33.5	251.0	87.6	1.6	26.5	107.2	4.2
				-4.2	100.0	6.0	21.6	44.1	5560.3	85.0	10.0	12.6	1342.1

Table 9. 12-Second Firing Period Including Soakback Data (Half Sec PO) (Continued)

TIME (HOURS)	MIN. RC PROD.=	AT NODE NO.	COMPUTING CYCLE	SYSTEM TEMPERATURES, DEG. F									
.0000	1.3888E-04	0	0	59.0	59.0	1621.5	1033.5	680.2	493.1	305.9	81.5	408.9	92.3
				90.3	61.1	61.0	475.5	240.6	198.3	167.3	395.0	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1500.0	266.0	14.7	27.3
				561.4	79.5	446.3	112.3	2.8	.0	2.7	2.7	.0	15.1
				.0	100.0	6.0	.0	.0	.0	85.0	10.0	.0	4.7
.0001	1.3888E-04	0	4	59.0	59.0	1621.5	1214.4	891.7	800.3	800.3	81.9	407.3	92.6
				90.6	61.1	61.1	474.9	240.9	198.5	167.9	395.4	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1490.9	247.7	14.7	24.0
				561.3	65.1	365.6	112.3	36.4	47.1	2.6	5.3	1.1	10.9
				.6	1569.7	6.0	15.4	12.4	702.7	85.0	10.0	17.6	40.5
.0003	1.3888E-04	0	8	59.0	59.0	1621.5	1219.5	905.7	797.3	797.3	82.4	414.1	93.3
				91.3	61.2	61.1	479.6	243.9	201.4	170.1	404.3	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1444.5	242.5	14.7	25.0
				561.0	50.2	281.8	112.2	97.5	69.6	2.5	10.0	5.3	8.7
				1.6	371.3	6.0	16.9	21.2	1342.4	85.0	10.0	16.1	156.4
.0004	1.3888E-04	0	12	59.0	59.0	1621.5	1203.4	880.0	759.8	759.8	82.9	430.7	94.3
				92.2	61.3	61.2	490.8	250.1	207.2	173.9	421.2	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1397.8	230.2	14.7	24.8
				560.6	44.3	248.5	105.7	130.8	75.6	2.4	12.8	11.2	7.6
				2.3	184.9	6.0	18.3	25.2	1782.7	85.0	10.0	14.8	262.5
.0006	1.3888E-04	0	16	59.0	59.0	1621.5	1180.0	841.2	714.4	714.4	83.4	453.0	95.5
				93.4	61.4	61.3	506.7	258.3	214.8	178.7	440.9	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1359.5	217.4	14.7	24.3
				560.3	44.0	246.4	88.2	147.2	78.5	2.3	14.8	18.3	7.4
				2.8	124.8	6.0	18.0	29.6	2134.8	85.0	10.0	15.1	352.5
.0007	1.3888E-04	0	20	59.0	59.0	1621.5	1164.8	816.2	685.5	685.5	83.9	478.5	97.0
				94.7	61.4	61.4	526.1	268.0	223.6	184.2	461.2	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1326.1	208.0	14.7	23.8
				560.1	43.6	244.4	77.3	158.0	80.3	2.2	16.3	26.1	7.2
				3.2	89.1	6.0	17.8	32.8	2426.1	85.0	10.0	15.2	432.7
.0008	1.3888E-04	0	24	59.0	59.0	1621.5	1148.4	788.8	654.8	654.8	84.5	505.9	98.6
				96.3	61.5	61.4	548.4	279.0	233.3	190.4	480.7	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1293.9	198.6	14.7	23.1
				559.8	43.6	244.0	67.9	165.9	81.9	2.2	17.9	34.7	7.0
				.8	640.9	6.0	17.4	37.1	2848.2	85.0	10.0	15.6	527.8

Table 9. 12-Second Firing Period Including Soakback Data (Half Sec PO) (Continued)

TIME (HOURS)	MIN. RC PROD.=	AT NODE NO.	COMPUTING CYCLE	SYSTEM TEMPERATURES, DEG. F									
.0010	1.3888E-04	0	28	59.0	59.0	1621.5	1130.4	759.7	621.7	621.7	85.2	535.8	100.5
				98.1	61.6	61.5	574.9	291.8	244.4	197.4	498.4	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1242.2	186.2	14.7	22.2
				559.3	42.7	239.1	57.8	178.9	83.6	2.1	19.9	44.3	6.6
				.4	1443.3	6.0	17.4	41.0	3334.7	85.0	10.0	15.6	666.2
.0011	1.3888E-04	0	32	59.0	59.0	1621.5	1115.5	735.9	595.2	595.2	85.8	566.8	102.7
				100.2	61.7	61.6	605.3	306.3	256.6	205.3	513.0	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1190.5	175.0	14.7	21.3
				558.7	41.9	234.3	49.9	189.7	84.9	1.9	21.7	54.8	6.2
				-.2	100.0	6.0	17.6	44.4	3834.1	85.0	10.0	15.5	814.5
.0012	1.3888E-04	0	36	59.0	59.0	1621.5	1101.9	714.1	571.4	571.4	86.6	597.4	105.2
				102.6	61.8	61.7	638.9	322.3	269.7	214.0	523.6	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1137.6	164.2	14.7	20.4
				558.1	41.2	229.7	43.4	199.1	86.0	1.8	23.4	66.2	5.8
				-1.3	100.0	6.0	17.7	47.7	4390.3	85.0	10.0	15.3	980.5
.0014	1.3888E-04	0	40	59.0	59.0	1621.5	1088.6	692.9	548.6	548.6	87.3	626.2	108.0
				105.4	61.9	61.8	675.4	339.7	283.6	223.5	529.3	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1080.1	153.1	14.7	19.4
				557.4	40.3	224.4	37.5	208.5	86.9	1.7	25.2	78.4	5.4
				-2.7	100.0	6.0	17.9	50.6	5030.4	85.0	10.0	15.2	1176.3
.0015	1.3888E-04	0	44	59.0	59.0	1621.5	1074.3	670.4	524.8	524.8	88.1	651.5	111.3
				108.6	62.1	61.9	713.9	358.4	297.9	233.7	528.9	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1016.8	141.3	14.7	18.2
				556.5	39.2	217.9	32.2	218.6	87.8	1.6	27.0	91.6	4.9
				-4.8	100.0	6.0	18.2	53.3	5807.1	85.0	10.0	14.9	1415.7
.0017	1.3888E-04	0	48	59.0	59.0	1621.5	687.6	508.2	477.2	477.2	89.0	651.4	112.7
				109.9	62.2	62.1	721.1	362.9	300.9	236.9	526.8	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	14.7	14.7	14.7	.0
				.0	.0	.0	.0	.0	.0	.0	.0	95.0	.0
				.0	.0	6.0	.0	.0	.0	85.0	10.0	.0	.0
.0018	1.3888E-04	0	52	59.0	59.0	1621.5	682.0	504.1	473.0	473.0	89.8	643.7	113.4
				110.5	62.3	62.2	717.5	362.5	300.2	237.7	525.4	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	14.7	14.7	14.7	.0
				.0	.0	.0	.0	.0	.0	.0	.0	95.0	.0
				.0	.0	6.0	.0	.0	.0	85.0	10.0	.0	.0

Table 9. 12-Second Firing Period Including Soakback Data (Half Sec PO) (Continued)

TIME (HOURS)	MIN. RC PROD.= AT NODE NO.		COMPUTING CYCLE	SYSTEM TEMPERATURES, DEG. F									
.0000	1.3888E-04	0	0	59.0	59.0	1621.5	1082.6	745.1	558.7	372.3	110.2	461.1	132.1
				125.4	66.8	66.3	619.1	349.1	278.4	255.2	486.5	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1500.0	266.0	14.7	27.3
				561.4	79.5	446.4	112.3	2.7	.0	2.7	2.7	.0	15.1
				.0	100.0	6.0	.0	.0	.0	85.0	10.0	.0	4.8
.0001	1.3888E-04	0	4	59.0	59.0	1621.5	1216.8	895.6	805.4	805.4	110.5	459.1	132.6
				125.7	66.9	66.5	617.7	349.1	278.3	255.7	486.5	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1490.9	248.4	14.7	24.0
				561.3	65.7	368.7	112.3	33.2	47.1	2.6	5.3	1.1	11.0
				.6	1580.2	6.0	15.3	12.6	705.5	85.0	10.0	17.8	40.6
.0003	1.3888E-04	0	8	59.0	59.0	1621.5	1225.6	915.6	810.3	810.3	111.0	464.9	133.4
				126.4	67.1	66.6	620.6	351.5	280.6	257.6	493.5	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1444.0	244.2	14.7	25.0
				561.0	51.6	289.7	112.2	89.4	69.7	2.5	10.0	5.3	9.0
				1.6	379.1	6.0	16.4	22.0	1359.9	85.0	10.0	16.6	158.6
.0004	1.3888E-04	0	12	59.0	59.0	1621.5	1209.8	889.9	773.3	773.3	111.6	480.2	134.5
				127.4	67.2	66.8	629.0	356.6	285.6	261.0	507.0	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1395.5	231.6	14.7	24.7
				560.6	46.3	259.7	104.1	120.9	75.9	2.4	13.0	11.3	8.0
				2.3	191.8	6.0	17.4	26.8	1820.1	85.0	10.0	15.6	269.4
.0006	1.3888E-04	0	16	59.0	59.0	1621.5	1186.9	852.0	728.9	728.9	112.1	500.9	135.9
				128.6	67.4	66.9	641.4	363.5	292.1	265.2	522.4	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1354.8	218.5	14.7	24.2
				560.3	46.2	258.7	86.2	136.5	78.9	2.3	15.0	18.5	7.8
				2.9	129.3	6.0	17.0	31.7	2193.4	85.0	10.0	15.9	365.6
.0007	1.3888E-04	0	20	59.0	59.0	1621.5	1172.0	827.4	700.6	700.6	112.7	524.9	137.4
				130.1	67.6	67.1	656.7	371.7	299.8	270.1	537.6	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1319.1	208.7	14.7	23.7
				560.0	45.9	257.1	75.2	147.0	80.7	2.2	16.6	26.5	7.5
				3.3	92.0	6.0	16.9	35.4	2503.1	85.0	10.0	16.1	451.9
.0008	1.3888E-04	0	24	59.0	59.0	1621.5	1153.0	795.8	665.1	665.1	113.3	551.1	139.2
				131.7	67.8	67.2	674.8	381.0	308.4	275.6	551.4	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1277.8	197.3	14.7	22.8
				559.6	45.8	256.2	64.4	156.5	82.5	2.1	18.5	35.3	7.2
				.7	826.5	6.0	16.4	40.6	3012.1	85.0	10.0	16.5	570.9

Table 9. 12-Second Firing Period Including Soakback Data (Half Sec PO) (Continued)

TIME (HOURS)	MIN. RC PROD.=	AT NODE NO.	COMPUTING CYCLE	SYSTEM TEMPERATURES, DEG. F									
.0010	1.3888E-04	0	28	59.0	59.0	1621.5	1135.7	768.1	633.9	633.9	114.0	579.6	141.3
				133.6	67.9	67.4	696.7	391.9	318.2	281.9	562.7	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1223.2	184.7	14.7	21.9
				559.1	45.0	251.6	54.6	168.8	84.1	2.0	20.6	45.2	6.8
				.2	2883.7	6.0	16.5	45.0	3532.7	85.0	10.0	16.5	722.1
.0011	1.3888E-04	0	32	59.0	59.0	1621.5	1121.1	744.8	608.1	608.1	114.7	608.9	143.6
				135.9	68.1	67.6	721.7	404.2	328.8	288.8	570.2	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1168.3	173.0	14.7	20.9
				558.5	44.2	247.0	46.9	179.1	85.4	1.9	22.5	56.1	6.4
				-.7	100.0	6.0	16.5	48.9	4080.1	85.0	10.0	16.4	885.1
.0012	1.3888E-04	0	36	59.0	59.0	1621.5	1107.1	722.7	584.2	584.2	115.4	637.3	146.3
				138.4	68.3	67.7	749.3	417.7	340.2	296.5	573.3	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1110.3	161.4	14.7	19.9
				557.8	43.4	242.2	40.4	188.8	86.5	1.8	24.3	67.9	6.0
				-1.9	100.0	6.0	16.7	52.5	4702.1	85.0	10.0	16.3	1073.7
.0014	1.3888E-04	0	40	59.0	59.0	1621.5	1093.0	700.5	560.6	560.6	116.2	663.4	149.4
				141.4	68.5	67.9	779.0	432.2	352.1	304.7	571.0	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	1047.7	149.5	14.7	18.8
				557.0	42.4	236.4	34.6	198.6	87.4	1.6	26.1	80.6	5.5
				-3.8	100.0	6.0	16.9	55.8	5434.2	85.0	10.0	16.1	1298.4
.0015	1.3888E-04	0	44	59.0	59.0	1621.5	741.2	561.9	520.7	520.7	117.0	678.4	152.2
				144.0	68.7	68.1	801.2	443.4	360.8	311.3	565.1	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	14.7	14.7	14.7	.0
				.0	.0	.0	.0	.0	.0	.0	.0	90.8	.0
				.0	.0	6.0	.0	.0	.0	85.0	10.0	.0	.0
.0017	1.3888E-04	0	48	59.0	59.0	1621.5	735.4	557.8	516.3	516.3	117.9	670.7	152.9
				144.6	68.9	68.3	797.3	442.8	359.8	311.8	563.8	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	14.7	14.7	14.7	.0
				.0	.0	.0	.0	.0	.0	.0	.0	90.8	.0
				.0	.0	6.0	.0	.0	.0	85.0	10.0	.0	.0
.0018	1.3888E-04	0	52	59.0	59.0	1621.5	729.7	553.7	512.1	512.1	118.7	663.2	153.7
				145.1	69.1	68.5	793.4	442.2	358.8	312.4	562.6	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	59.0
				60.6	12.7	15.5	56.7	39.1	1500.0	14.7	14.7	14.7	.0
				.0	.0	.0	.0	.0	.0	.0	.0	90.8	.0
				.0	.0	6.0	.0	.0	.0	85.0	10.0	.0	.0

Table 9. 12-Second Firing Period Including Soakback Data (Half Sec PO) (Continued)

TIME (HOURS)	MIN. RC PROD.=	AT NODE NO.	COMPUTING CYCLE	SYSTEM TEMPERATURES, DEG. F									
.0000	1.3888E-04	0	0	130.0	130.0	1633.3	881.7	505.8	317.9	130.0	130.0	130.0	130.0
				130.0	130.0	130.0	130.0	130.0	130.0	130.0	130.0	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1500.0	264.3	14.7	26.8
				570.2	79.5	453.1	114.0	3.1	.0	2.7	2.7	.0	15.1
				.0	100.0	6.0	.0	.0	.0	85.0	10.0	.0	4.6
.0001	1.3888E-04	0	4	130.0	130.0	1633.3	1211.3	879.7	784.2	784.2	130.0	132.1	130.0
				130.0	130.0	130.0	131.4	130.5	130.5	130.2	131.9	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1491.0	244.1	14.7	23.6
				570.1	63.8	363.8	114.0	44.9	47.4	2.6	5.3	1.1	10.6
				.4	1953.5	6.0	15.7	12.1	699.1	85.0	10.0	18.3	40.1
.0003	1.3888E-04	0	8	130.0	130.0	1633.3	1204.6	877.3	760.4	760.4	130.0	147.4	130.3
				130.3	130.0	130.0	141.0	134.1	133.8	131.9	147.2	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1446.5	236.4	14.7	24.7
				569.8	46.7	266.0	114.0	119.6	70.2	2.5	9.8	5.2	8.1
				1.2	455.0	6.0	18.1	19.4	1322.7	85.0	10.0	15.9	152.5
.0004	1.3888E-04	0	12	130.0	130.0	1633.3	1185.3	848.6	719.5	719.5	130.0	175.8	130.9
				130.9	130.0	130.0	159.6	141.1	140.1	135.1	174.5	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1402.6	224.3	14.7	24.5
				569.5	39.4	224.2	110.6	158.2	76.4	2.4	12.5	11.0	6.8
				1.8	223.4	6.0	20.4	22.0	1746.0	85.0	10.0	14.1	253.3
.0006	1.3888E-04	0	16	130.0	130.0	1633.3	1158.8	805.6	669.2	669.2	130.1	211.8	131.6
				131.6	130.0	130.0	184.6	150.2	148.0	139.2	207.5	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1367.1	211.5	14.7	24.0
				569.2	38.6	219.6	92.9	177.3	79.3	2.3	14.3	17.8	6.5
				2.2	154.1	6.0	20.3	25.4	2082.2	85.0	10.0	14.1	337.5
.0007	1.3888E-04	0	20	130.0	130.0	1633.3	1141.3	777.7	637.3	637.3	130.3	252.5	132.5
				132.5	130.0	130.0	214.4	160.8	157.1	144.0	242.6	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1335.8	202.1	14.7	23.6
				568.9	38.1	216.7	81.6	189.4	81.2	2.3	15.8	25.5	6.3
				2.5	113.1	6.0	20.2	28.1	2367.2	85.0	10.0	14.2	413.7
.0008	1.3888E-04	0	24	130.0	130.0	1633.3	1129.7	759.0	616.5	616.5	130.5	295.6	133.6
				133.6	130.0	130.0	247.9	172.8	167.0	149.4	278.1	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1308.6	195.0	14.7	23.2
				568.7	37.9	215.3	73.9	197.1	82.5	2.2	17.0	33.8	6.2
				2.8	86.7	6.0	20.1	30.4	2609.7	85.0	10.0	14.3	481.7

Table 9. 12-Second Firing Period Including Soakback Data (Half Sec PO) (Continued)

TIME (HOURS)	MIN. RC PROD.=	AT NODE NO.	COMPUTING CYCLE	SYSTEM TEMPERATURES, DEG. F									
.0010	1.3888E-04	0	28	130.0	130.0	1633.3	1119.0	741.5	597.4	597.4	130.7	339.6	134.9
				134.8	130.0	130.0	284.3	185.8	177.7	155.3	312.6	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1283.6	188.5	14.7	22.7
				568.4	37.9	215.6	67.4	201.9	83.6	2.1	18.1	42.6	6.1
				1.5	232.8	6.0	19.8	33.0	2906.7	85.0	10.0	14.5	553.4
.0011	1.3888E-04	0	32	130.0	130.0	1633.3	1106.7	721.8	575.8	575.8	131.1	384.6	136.3
				136.2	130.0	130.0	324.2	200.2	189.2	161.8	345.5	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1248.2	180.3	14.7	22.1
				568.1	37.6	213.6	60.2	209.5	84.8	2.1	19.5	52.1	5.8
				1.1	333.2	6.0	19.7	35.7	3256.5	85.0	10.0	14.6	651.3
.0012	1.3888E-04	0	36	130.0	130.0	1633.3	1095.9	704.4	557.1	557.1	131.5	429.8	137.9
				137.8	130.1	130.1	367.7	215.9	201.6	169.0	375.9	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1210.9	172.3	14.7	21.4
				567.7	37.3	211.9	53.9	216.1	85.8	2.0	20.9	62.3	5.6
				.7	563.6	6.0	19.6	38.3	3627.8	85.0	10.0	14.6	759.1
.0014	1.3888E-04	0	40	130.0	130.0	1633.3	1086.4	689.2	541.0	541.0	131.9	473.9	139.8
				139.7	130.1	130.1	414.3	232.9	214.7	176.8	402.9	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1172.0	164.6	14.7	20.7
				567.3	37.1	210.3	48.4	221.8	86.7	1.9	22.2	73.1	5.4
				.3	1618.4	6.0	19.6	40.8	4023.2	85.0	10.0	14.7	877.3
.0015	1.3888E-04	0	44	130.0	130.0	1633.3	1078.0	675.6	527.0	527.0	132.4	515.9	141.9
				141.8	130.1	130.1	463.4	251.1	228.4	185.2	425.9	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1131.7	157.1	14.7	20.0
				566.8	36.9	208.9	43.6	226.8	87.5	1.8	23.5	84.6	5.2
				-.3	100.0	6.0	19.5	43.3	4449.5	85.0	10.0	14.7	1007.0
.0017	1.3888E-04	0	48	130.0	130.0	1633.3	1069.8	662.2	513.3	513.3	133.0	554.7	144.2
				144.1	130.1	130.1	514.3	270.5	242.7	194.3	444.2	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1088.8	149.3	14.7	19.3
				566.3	36.6	207.3	39.1	231.6	88.3	1.7	24.8	96.8	4.9
				-1.2	100.0	6.0	19.5	45.8	4931.6	85.0	10.0	14.7	1155.3
.0018	1.3888E-04	0	52	130.0	130.0	1633.3	1060.5	647.1	497.8	497.8	133.7	589.4	146.9
				146.7	130.2	130.2	566.6	290.8	257.4	204.0	457.2	.0	-1.0
				-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1041.2	140.9	14.7	18.4
				565.6	36.2	204.9	34.7	237.0	89.0	1.6	26.2	109.6	4.7
				-3.2	100.0	6.0	19.5	48.4	5533.9	85.0	10.0	14.7	1335.2

Table 9. 12-Second Firing Period Including Soakback Data (Half Sec PO) (Continued)

TIME (HOURS)	MIN. RC PROD.=	AT NODE NO.	COMPUTING CYCLE	SYSTEM TEMPERATURES, DEG. F									
.0000	1.3888E-04	0	0	130.0	130.0	1633.3	1065.5	723.1	541.0	359.0	151.4	455.7	162.1
				160.3	132.0	132.0	533.6	301.3	257.9	231.0	430.7	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1500.0	264.3	14.7	26.8
				570.2	79.5	453.4	114.0	2.8	.0	2.7	2.7	.0	15.1
				.0	100.0	6.0	.0	.0	.0	85.0	10.0	.0	4.7
.0001	1.3888E-04	0	4	130.0	130.0	1633.3	1220.1	892.7	800.8	800.8	151.8	454.1	162.5
				160.5	132.1	132.0	532.9	301.5	258.1	231.5	431.0	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1491.0	246.5	14.7	23.6
				570.1	65.6	373.9	114.0	34.7	47.5	2.6	5.3	1.1	10.9
				.4	1996.5	6.0	15.1	12.6	708.2	85.0	10.0	19.0	40.4
.0003	1.3888E-04	0	8	130.0	130.0	1633.3	1226.7	909.7	802.3	802.3	152.2	460.5	163.1
				161.1	132.2	132.1	537.2	304.4	260.7	233.6	439.4	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1444.7	241.9	14.7	24.6
				569.8	51.1	291.4	114.0	93.6	70.8	2.5	10.0	5.3	8.9
				1.3	486.9	6.0	16.3	22.0	1378.7	85.0	10.0	17.6	159.7
.0004	1.3888E-04	0	12	130.0	130.0	1633.3	1208.7	880.9	761.7	761.7	152.7	476.5	164.1
				162.0	132.2	132.2	548.0	310.2	266.2	237.2	455.6	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1395.4	228.7	14.7	24.3
				569.4	45.6	259.5	105.5	127.2	77.2	2.4	13.0	11.3	7.8
				1.9	251.0	6.0	17.4	26.9	1864.4	85.0	10.0	16.5	275.3
.0006	1.3888E-04	0	16	130.0	130.0	1633.3	1183.5	839.3	713.3	713.3	153.2	498.2	165.3
				163.2	132.3	132.2	563.6	318.1	273.4	241.7	474.2	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1352.5	214.8	14.7	23.7
				569.1	45.3	257.8	86.6	144.3	80.4	2.3	15.2	18.5	7.6
				2.4	171.9	6.0	17.0	32.0	2269.2	85.0	10.0	16.9	379.1
.0007	1.3888E-04	0	20	130.0	130.0	1633.3	1166.7	811.9	682.0	682.0	153.7	523.3	166.7
				164.5	132.4	132.3	583.0	327.5	281.7	246.9	493.1	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1313.9	204.3	14.7	23.2
				568.7	44.9	255.6	74.8	156.0	82.4	2.2	16.9	26.6	7.3
				2.8	124.4	6.0	16.9	35.9	2614.0	85.0	10.0	17.0	475.0
.0008	1.3888E-04	0	24	130.0	130.0	1633.3	1152.0	787.8	655.0	655.0	154.3	550.2	168.3
				166.0	132.5	132.4	605.3	338.1	291.0	252.8	510.9	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1278.5	195.0	14.7	22.5
				568.4	44.8	254.4	65.9	164.3	83.8	2.1	18.4	35.5	7.1
				1.5	310.9	6.0	16.6	39.9	3007.7	85.0	10.0	17.3	574.6

Table 9. 12-Second Firing Period Including Soakback Data (Half Sec PO) (Continued)

TIME (HOURS)	MIN. RC PROD.=	AT NODE NO.	COMPUTING CYCLE	SYSTEM TEMPERATURES, DEG. F									
.0010	1.3888E-04	0	28	130.0	130.0	1633.3	1137.3	764.1	628.6	628.6	154.9	578.3	170.1
				167.8	132.6	132.5	630.9	350.1	301.2	259.3	526.5	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1233.4	184.5	14.7	21.7
				567.9	44.3	251.3	57.3	174.0	85.2	2.0	20.1	45.2	6.8
				1.0	499.1	6.0	16.6	43.7	3448.4	85.0	10.0	17.3	700.3
.0011	1.3888E-04	0	32	130.0	130.0	1633.3	1124.4	743.5	606.1	606.1	155.5	606.6	172.2
				169.8	132.7	132.6	659.5	363.4	312.1	266.5	538.9	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1186.9	174.6	14.7	20.9
				567.5	43.7	248.1	50.3	182.6	86.4	1.9	21.8	55.8	6.4
				.4	1180.5	6.0	16.6	47.2	3912.0	85.0	10.0	17.3	838.1
.0012	1.3888E-04	0	36	130.0	130.0	1633.3	1113.1	725.5	586.7	586.7	156.2	633.9	174.6
				172.1	132.8	132.7	690.5	377.9	323.7	274.3	547.6	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1139.5	165.1	14.7	20.1
				566.9	43.2	244.9	44.4	190.3	87.4	1.8	23.3	67.2	6.1
				-.2	100.0	6.0	16.6	50.4	4402.3	85.0	10.0	17.2	988.0
.0014	1.3888E-04	0	40	130.0	130.0	1633.3	1102.2	708.3	568.6	568.6	156.9	659.1	177.2
				174.6	132.9	132.8	723.2	393.3	335.8	282.6	552.2	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1090.4	155.7	14.7	19.2
				566.3	42.6	241.5	39.2	197.4	88.3	1.7	24.8	79.3	5.8
				-1.2	100.0	6.0	16.7	53.4	4946.9	85.0	10.0	17.2	1156.2
.0015	1.3888E-04	0	44	130.0	130.0	1633.3	1090.5	689.6	549.0	549.0	157.7	681.1	180.2
				177.5	133.0	132.9	757.3	409.4	348.0	291.4	552.0	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1037.0	145.7	14.7	18.3
				565.6	41.9	237.2	34.3	204.9	89.1	1.6	26.4	92.2	5.4
				-3.4	100.0	6.0	16.8	56.5	5620.4	85.0	10.0	17.1	1358.6
.0017	1.3888E-04	0	48	130.0	130.0	1633.3	731.2	553.1	521.3	521.3	158.5	686.8	182.1
				179.3	133.1	133.0	772.8	417.5	353.8	296.4	549.1	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	14.7	14.7	14.7	.0
				.0	.0	.0	.0	.0	.0	.0	.0	99.0	.0
				.0	.0	6.0	.0	.0	.0	85.0	10.0	.0	.0
.0018	1.3888E-04	0	52	130.0	130.0	1633.3	725.7	549.3	517.3	517.3	159.3	679.4	182.8
				179.9	133.2	133.1	769.2	417.2	353.1	297.1	547.9	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	14.7	14.7	14.7	.0
				.0	.0	.0	.0	.0	.0	.0	.0	99.0	.0
				.0	.0	6.0	.0	.0	.0	85.0	10.0	.0	.0

Table 9. 12-Second Firing Period Including Soakback Data (Half Sec PO) (Continued)

TIME (HOURS)	MIN. RC PROD.=	AT NODE NO.	COMPUTING CYCLE	SYSTEM TEMPERATURES, DEG. F									
.0000	1.3888E-04	0	0	130.0	130.0	1633.3	1112.4	784.8	603.1	421.4	178.5	505.1	200.8
				194.1	137.6	137.2	670.8	404.4	332.8	313.9	513.6	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1500.0	264.3	14.7	26.8
				570.2	79.5	453.5	114.0	2.6	.0	2.7	2.7	.0	15.1
				.0	100.0	6.0	.0	.0	.0	85.0	10.0	.0	4.8
.0001	1.3888E-04	0	4	130.0	130.0	1633.3	1222.5	896.4	805.6	805.6	178.9	503.2	201.2
				194.5	137.8	137.3	669.4	404.5	332.7	314.4	513.6	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1491.0	247.2	14.7	23.6
				570.1	66.1	376.9	114.0	31.6	47.6	2.6	5.3	1.1	11.0
				.4	2008.8	6.0	15.0	12.7	710.9	85.0	10.0	19.2	40.5
.0003	1.3888E-04	0	8	130.0	130.0	1633.3	1232.6	919.3	814.9	814.9	179.3	508.6	202.0
				195.1	137.9	137.5	672.0	406.6	334.8	316.1	520.3	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1444.1	243.5	14.7	24.5
				569.8	52.5	299.1	114.0	85.7	71.0	2.5	10.0	5.3	9.1
				1.3	496.1	6.0	15.8	22.9	1395.4	85.0	10.0	18.2	161.8
.0004	1.3888E-04	0	12	130.0	130.0	1633.3	1215.2	890.9	775.1	775.1	179.8	523.3	203.0
				196.1	138.1	137.6	679.9	411.4	339.5	319.2	533.3	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1393.2	230.0	14.7	24.2
				569.4	47.5	270.5	104.0	117.4	77.5	2.4	13.1	11.4	8.1
				1.9	259.0	6.0	16.6	28.5	1900.8	85.0	10.0	17.3	282.1
.0006	1.3888E-04	0	16	130.0	130.0	1633.3	1190.6	850.3	728.0	728.0	180.3	543.5	204.4
				197.3	138.2	137.7	691.9	417.9	345.7	323.2	547.8	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1347.9	215.9	14.7	23.6
				569.0	47.4	269.9	84.8	133.6	80.7	2.3	15.4	18.7	7.9
				2.4	177.1	6.0	16.2	34.2	2326.8	85.0	10.0	17.7	392.2
.0007	1.3888E-04	0	20	130.0	130.0	1633.3	1174.1	823.6	697.5	697.5	180.9	566.9	205.9
				198.6	138.4	137.9	707.1	425.7	352.9	327.8	561.9	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1307.1	205.1	14.7	23.0
				568.7	47.2	268.3	72.9	144.9	82.7	2.2	17.2	26.9	7.7
				2.9	127.9	6.0	16.0	38.6	2690.8	85.0	10.0	17.9	494.5
.0008	1.3888E-04	0	24	130.0	130.0	1633.3	1158.2	797.4	668.3	668.3	181.5	592.2	207.6
				200.2	138.6	138.1	724.8	434.6	360.9	332.9	574.3	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1266.0	194.6	14.7	22.3
				568.3	47.0	267.0	63.2	153.7	84.3	2.1	18.9	36.0	7.4
				1.3	373.1	6.0	15.8	43.3	3143.5	85.0	10.0	18.2	610.2

Table 9. 12-Second Firing Period Including Soakback Data (Half Sec PO) (Concluded)

TIME (HOURS)	MIN. RC PROD.=	AT NODE NO.	COMPUTING CYCLE	SYSTEM TEMPERATURES, DEG. F									
.0010	1.3888E-04	0	28	130.0	130.0	1633.3	1143.5	774.0	642.4	642.4	182.1	618.7	209.6
				202.1	138.8	138.2	745.4	444.6	369.7	338.6	583.9	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1217.6	183.6	14.7	21.4
				567.8	46.5	264.1	54.7	163.3	85.7	2.0	20.7	46.1	7.0
				.8	670.0	6.0	15.7	47.5	3620.8	85.0	10.0	18.3	748.6
.0011	1.3888E-04	0	32	130.0	130.0	1633.3	1130.7	753.7	620.3	620.3	182.8	645.1	211.8
				204.2	138.9	138.4	768.4	455.6	379.1	344.8	590.1	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1167.7	173.2	14.7	20.6
				567.2	46.0	260.9	47.7	171.8	86.8	1.9	22.4	57.0	6.7
				.2	2764.8	6.0	15.7	51.4	4122.5	85.0	10.0	18.3	900.0
.0012	1.3888E-04	0	36	130.0	130.0	1633.3	1119.1	735.4	600.9	600.9	183.5	670.3	214.3
				206.5	139.1	138.6	793.2	467.4	389.0	351.5	592.4	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1117.1	163.2	14.7	19.7
				566.6	45.4	257.5	41.9	179.4	87.8	1.8	24.0	68.7	6.3
				-.7	100.0	6.0	15.7	54.9	4661.6	85.0	10.0	18.2	1065.7
.0014	1.3888E-04	0	40	130.0	130.0	1633.3	1107.6	717.4	582.0	582.0	184.2	692.9	217.1
				209.2	139.3	138.7	819.4	479.8	399.0	358.5	590.5	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1063.9	153.1	14.7	18.8
				565.9	44.8	253.6	36.7	187.0	88.7	1.7	25.6	81.2	5.9
				-2.2	100.0	6.0	15.8	58.3	5281.6	85.0	10.0	18.1	1255.7
.0015	1.3888E-04	0	44	130.0	130.0	1633.3	1093.6	695.7	559.4	559.4	185.0	711.8	220.2
				212.2	139.5	138.9	846.4	492.6	409.0	365.9	583.5	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	1002.8	141.6	14.7	17.6
				565.0	43.9	248.1	31.6	195.8	89.5	1.5	27.4	94.5	5.4
				-5.1	100.0	6.0	16.0	61.7	6097.1	85.0	10.0	18.0	1501.7
.0017	1.3888E-04	0	48	130.0	130.0	1633.3	774.9	599.2	557.3	557.3	185.8	704.4	220.9
				212.7	139.7	139.1	842.5	492.1	408.1	366.4	582.4	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	14.7	14.7	14.7	.0
				.0	.0	.0	.0	.0	.0	.0	.0	94.5	.0
				.0	.0	6.0	.0	.0	.0	85.0	10.0	.0	.0
.0018	1.3888E-04	0	52	130.0	130.0	1633.3	769.3	595.4	553.2	553.2	186.6	697.2	221.6
				213.3	139.9	139.3	838.6	491.5	407.2	366.9	581.3	.0	.0
				.0	.0	.0	.0	.0	.0	.0	.0	.0	130.0
				60.4	12.7	15.3	56.7	39.1	1500.0	14.7	14.7	14.7	.0
				.0	.0	.0	.0	.0	.0	.0	.0	94.5	.0
				.0	.0	6.0	.0	.0	.0	85.0	10.0	.0	.0

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